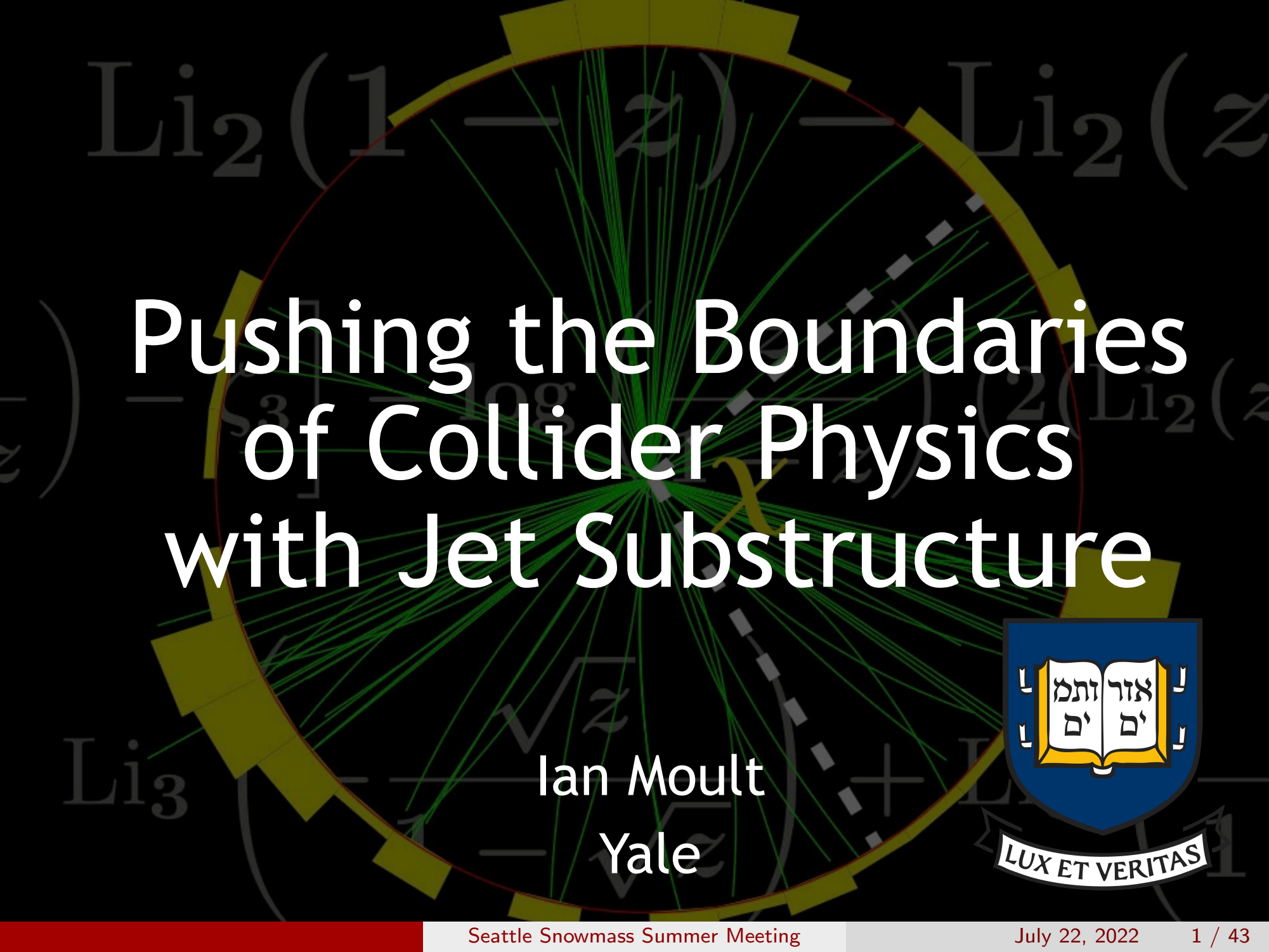
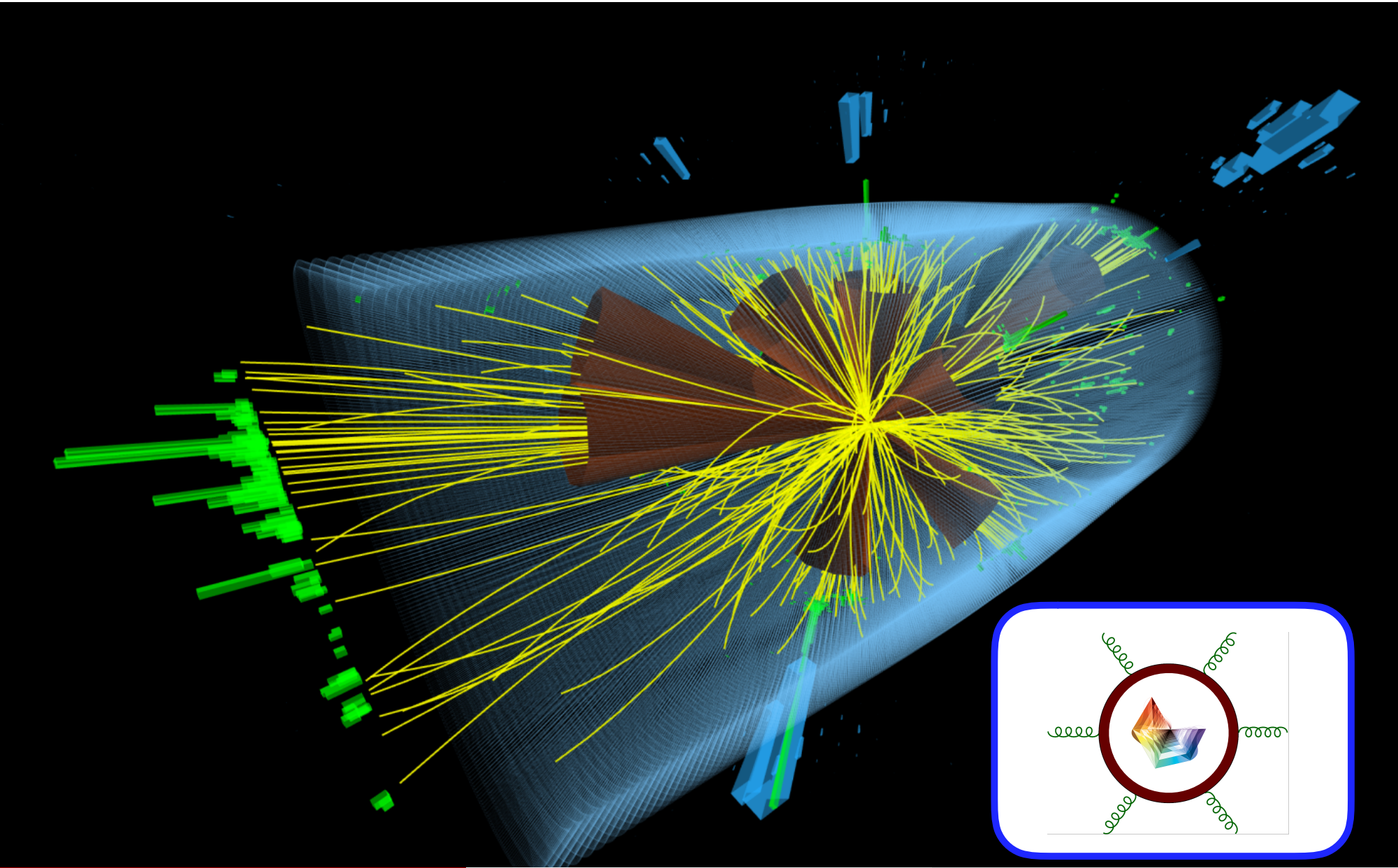


Pushing the Boundaries of Collider Physics with Jet Substructure

Ian Moult
Yale

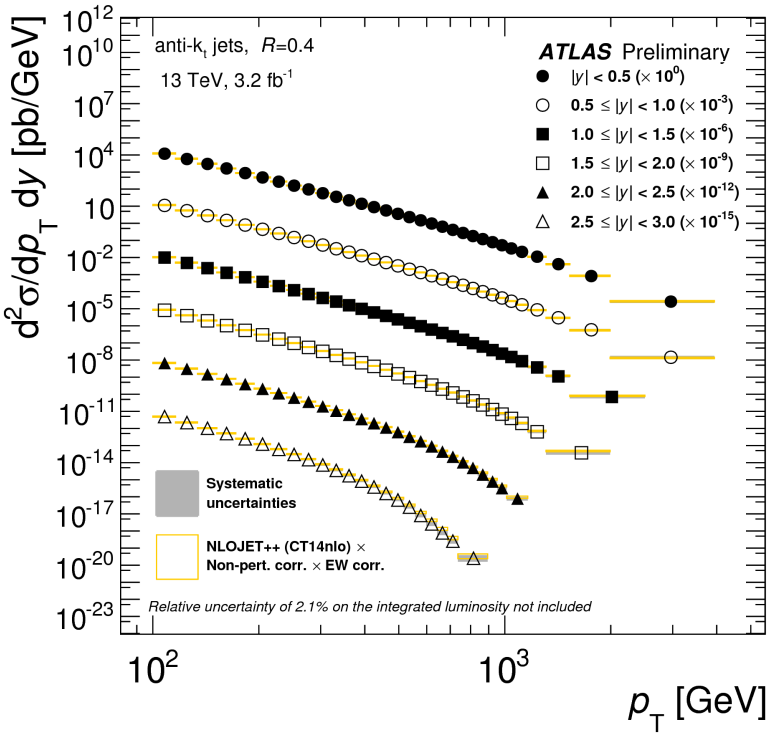
Jets at the LHC

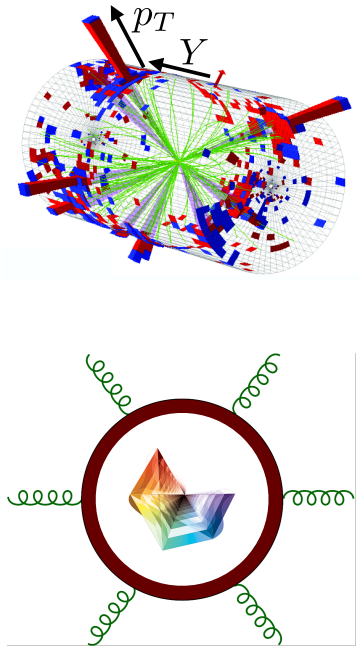


Jets at the LHC

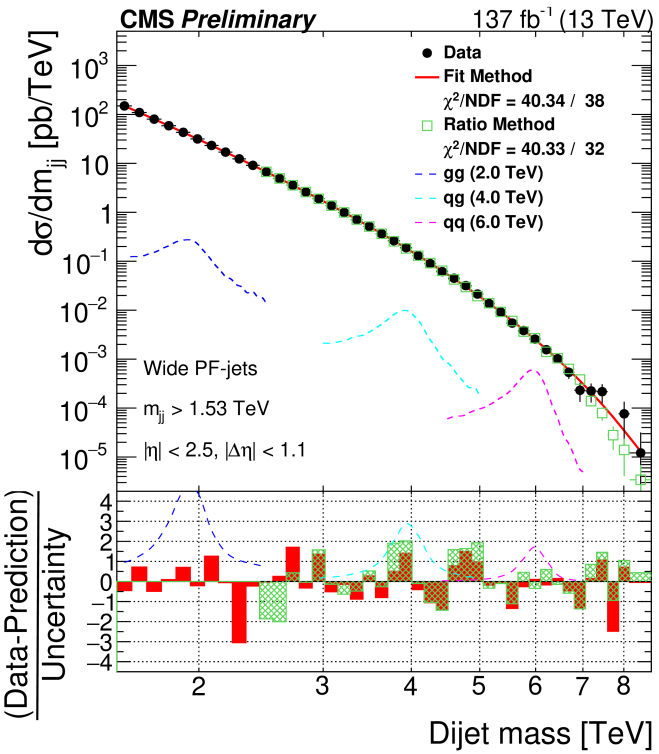
- Obtaining a precise description of jet cross sections has been a significant driver of theory developments in Quantum Field Theory.

Jet Kinematic Distributions



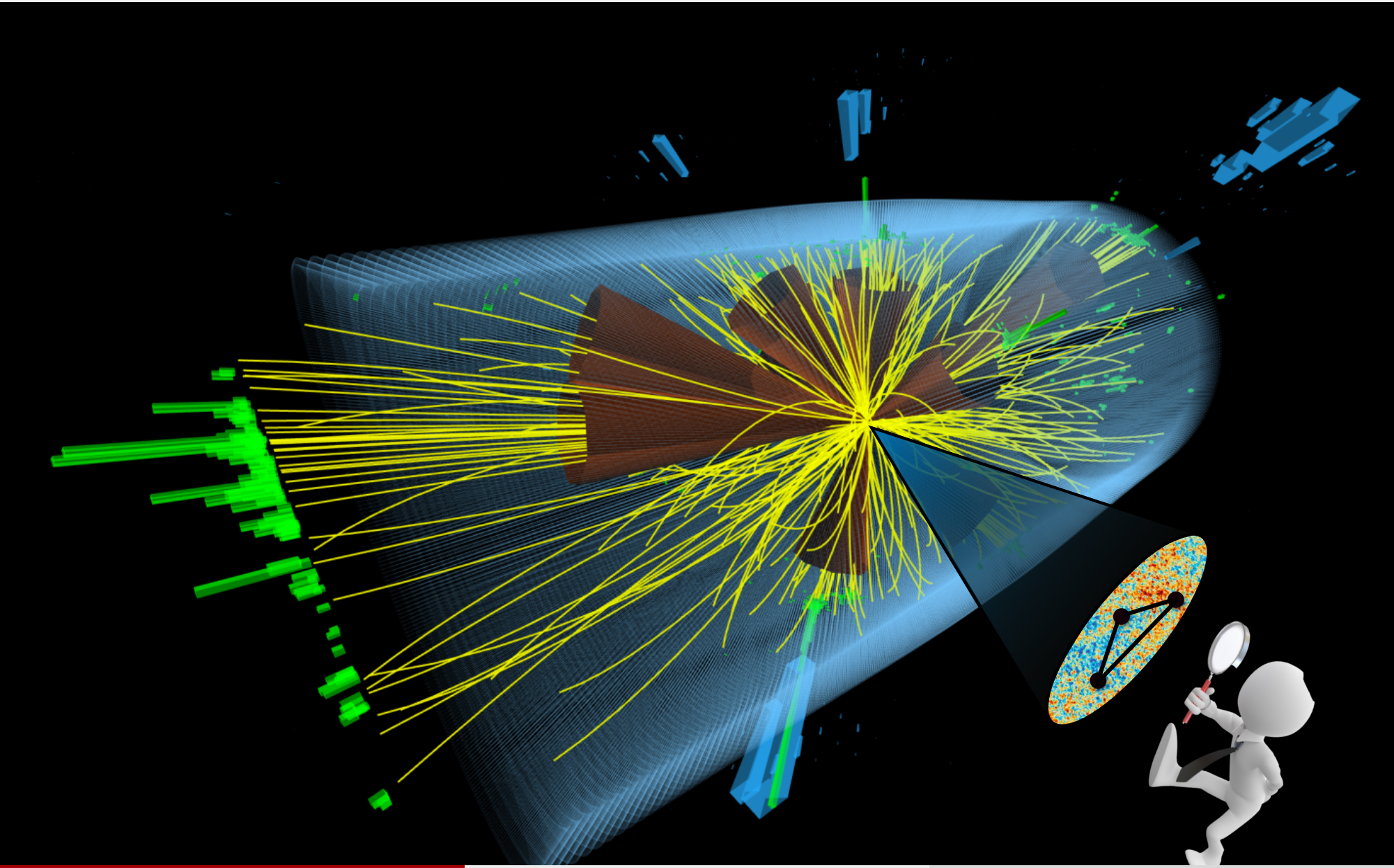


Dijet Mass



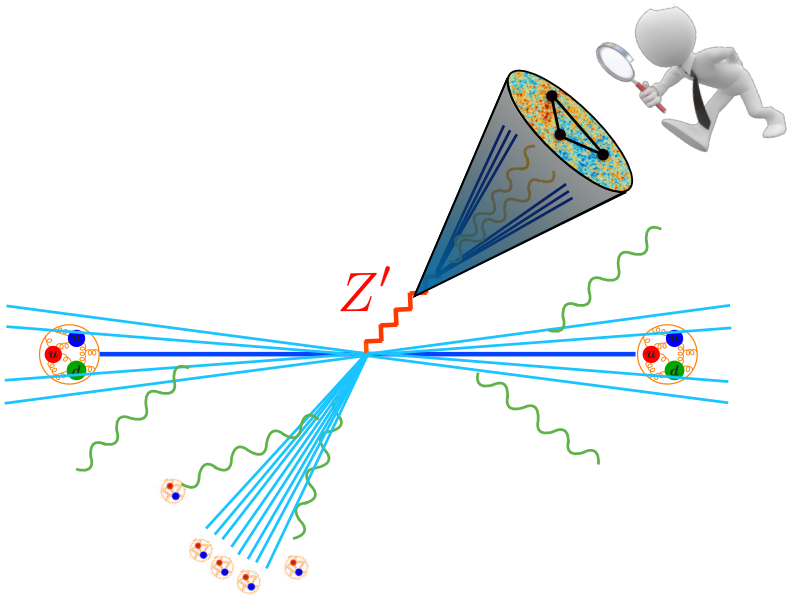
- Enables precision tests of QCD and searches for new physics.

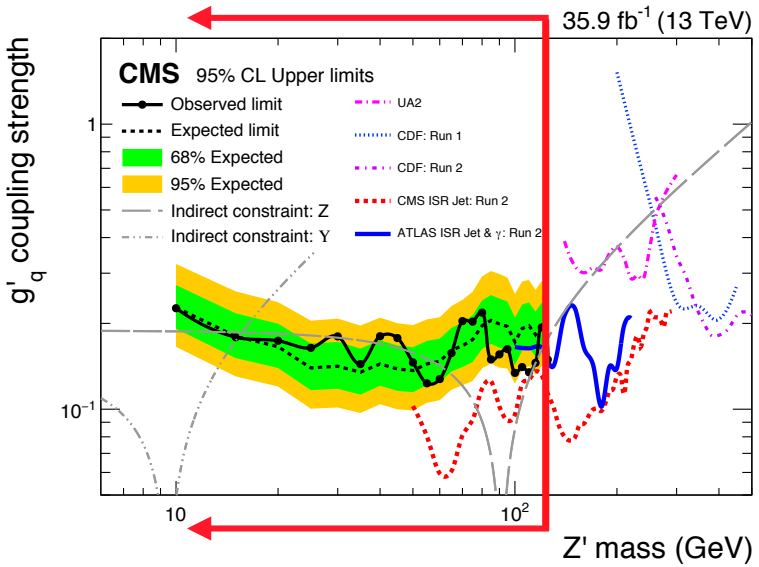
Jet Substructure!



Jet Substructure: Searches

- Jet Substructure uses the internal structure of jets to provide qualitatively new ways to study physics at colliders.

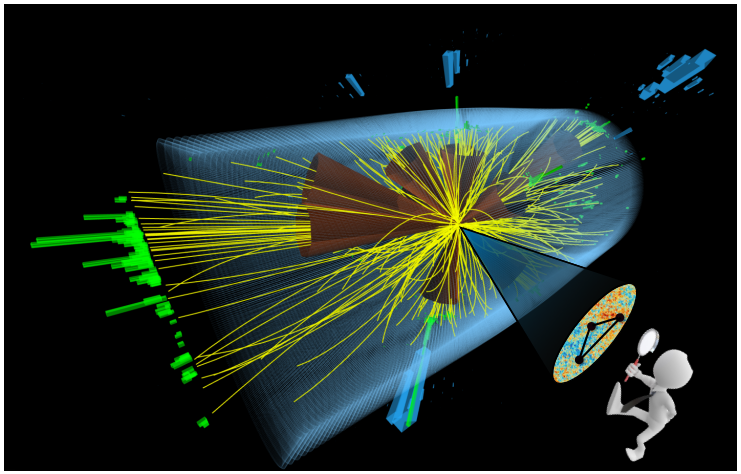


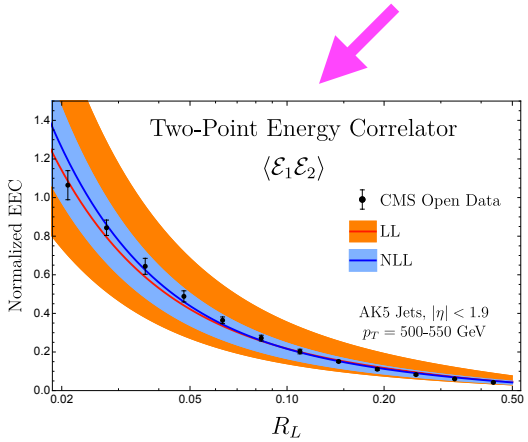


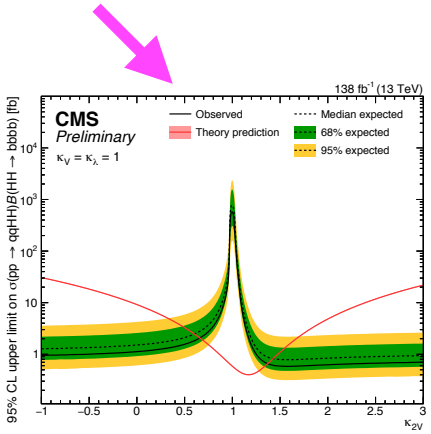
- Its introduction in 2008 by Butterworth, Davison, Rubin and Salam, along with anti-k_T by Cacciari, Soyez, Salam reinvigorated the study of jets in QCD.

The Boundaries of Collider Physics

- Progress in formal theory and data science have transformed jet substructure, enabling new tests of QFT, and ever improving ways to search for fundamental physics.

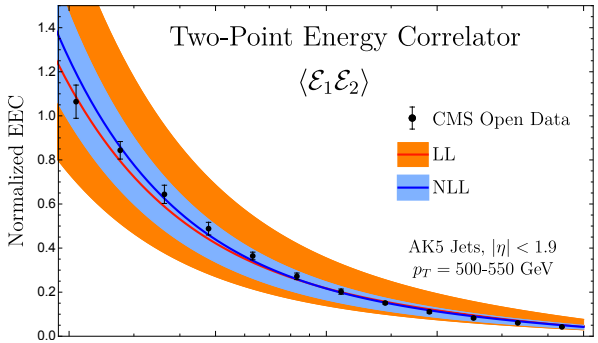




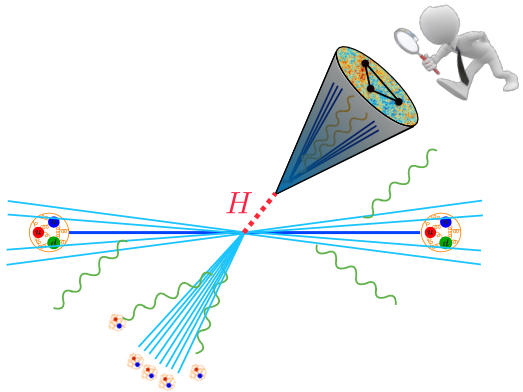


Outline

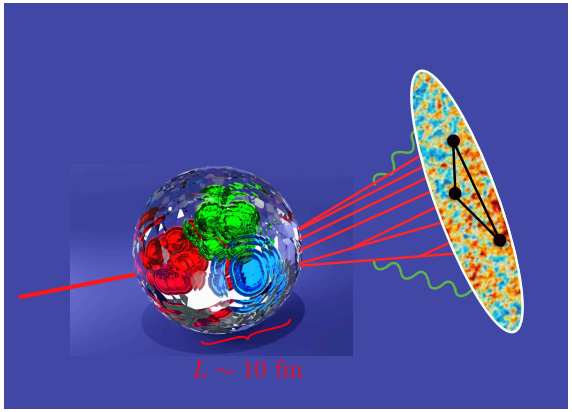
- Field Theoretic Foundations and Precision Jet Substructure



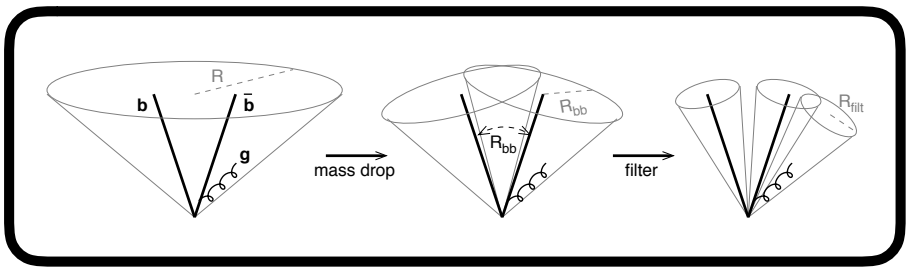
- Data Science and Searches

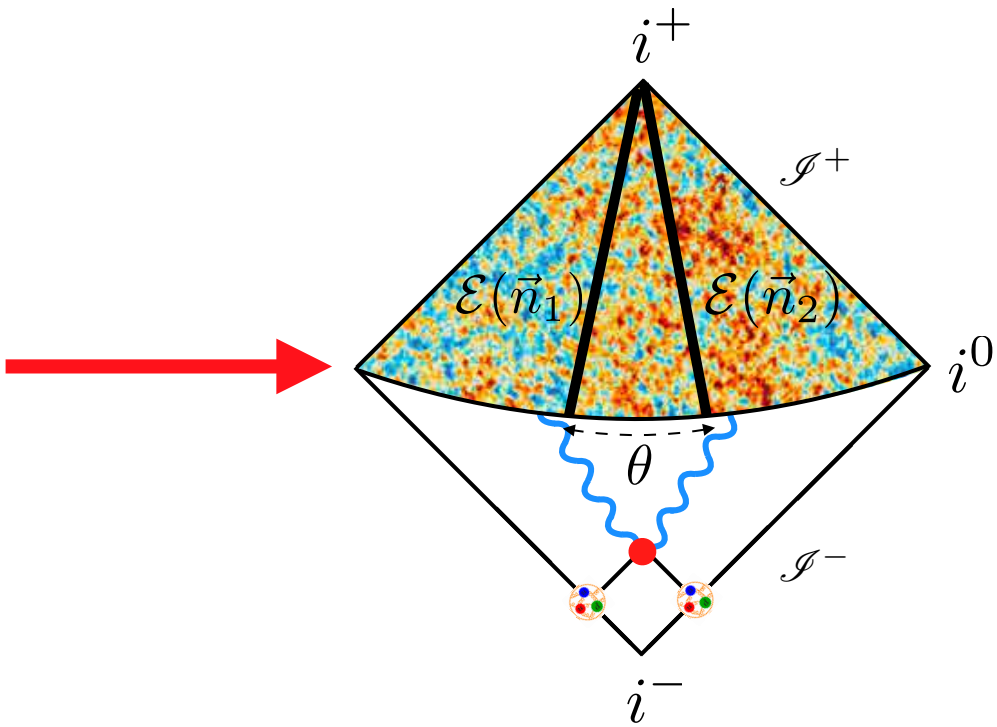


- The Frontiers of QCD



From Phenomenological Procedures to Field Theoretic Observables

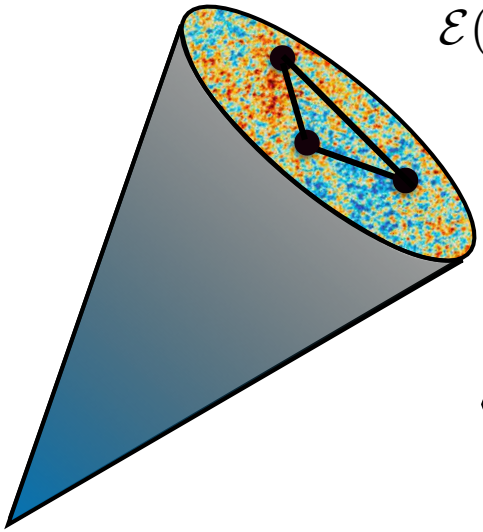




Insights from Conformal Field Theory

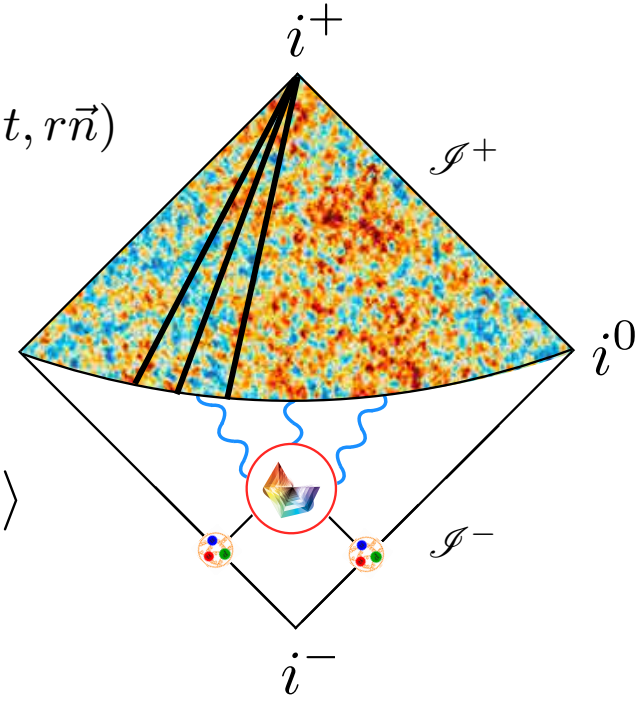
- Motivated by the phenomenological importance of jet substructure, one can give it a proper field theoretic foundation. [Kravchuk, Simmons-Duffin]
- Achieved through the introduction of light-ray operators. [Hofman, Maldacena] [Korchemsky, Sterman]

[Basham, Brown, Ellis, Love]



$$\mathcal{E}(\vec{n}) = \lim_{r\to\infty} r^2 \int_0^\infty dt n^i T_{0i}(t, r\vec{n})$$

$$\langle\Psi|\mathcal{E}(\hat{n}_1)\cdots\mathcal{E}(\hat{n}_k)|\Psi\rangle$$

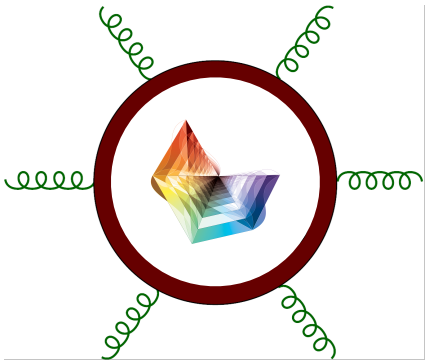


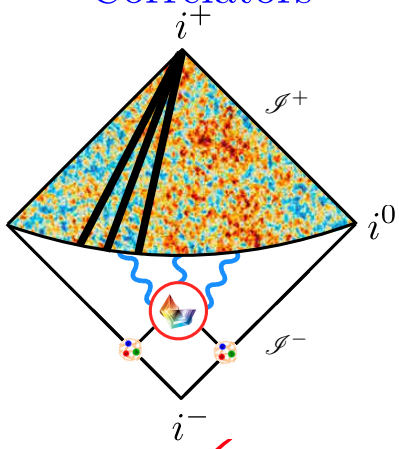
- From the perspective of QFT, jet substructure is the study of correlation functions of energy flow operators.

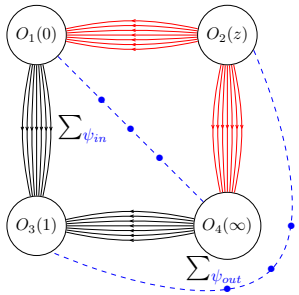
Energy Correlators

- Correlation functions of energy flow operators take an interesting intermediate position between amplitudes and correlation functions.

	Amplitudes	Energy Correlators	Correlation Functions
Asymptotic States	✓	✓	
IR Finite		✓	✓





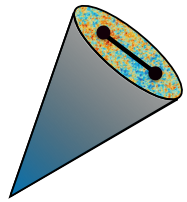


- Calculating physical observables in QFT has traditionally been a fruitful approach to developing a deeper understanding.

[Dixon et al.]
[Yan, Zhang]
[Belitsky et al.]

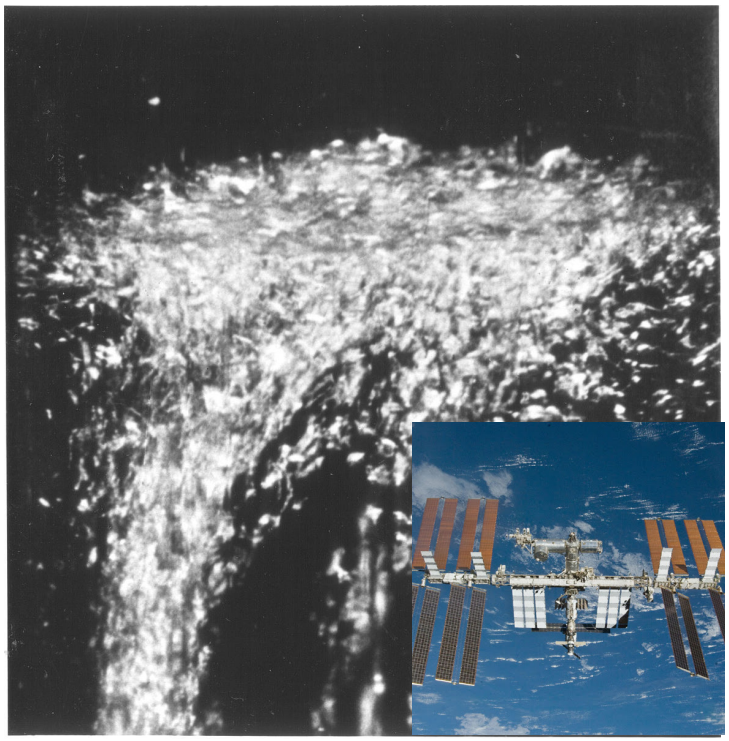
Scaling Behavior in QFT

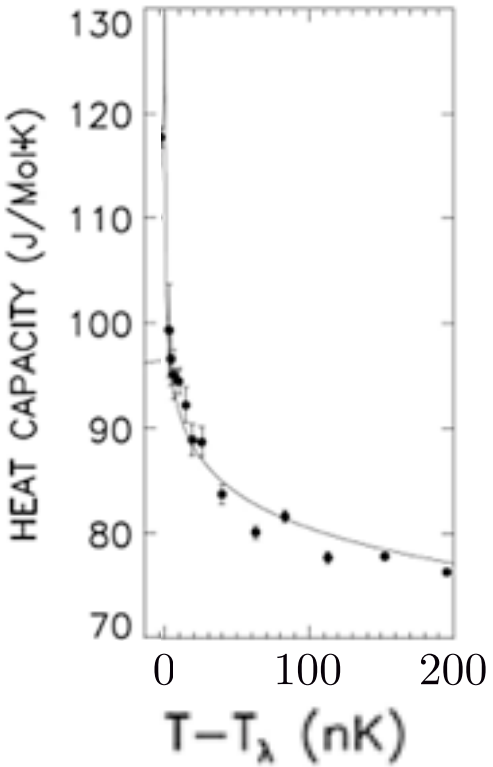
- Why is jet substructure theoretically interesting?



- QFTs exhibit universal behavior as operators are brought together.

λ-point of Helium

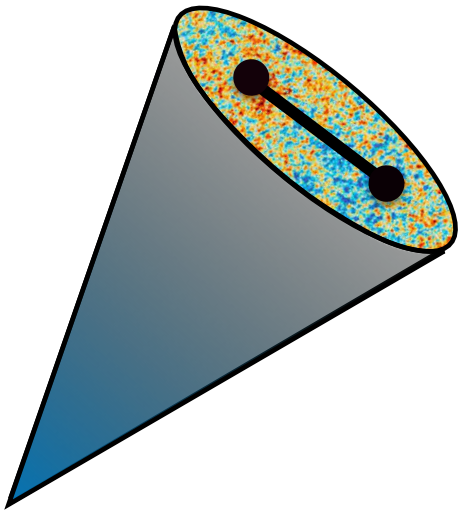


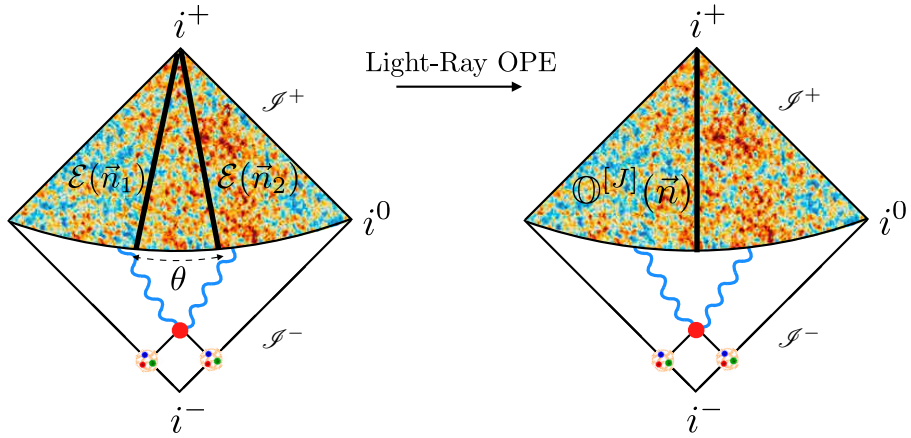


$$\mathcal{O}(x)\mathcal{O}(0) = \sum x^{\gamma_i} c_i \mathcal{O}_i$$

The OPE Limit of Lightray Operators

- Energy flow operators also admit an OPE!
- The substructure of jets is determined by the OPE structure of lightray operators.





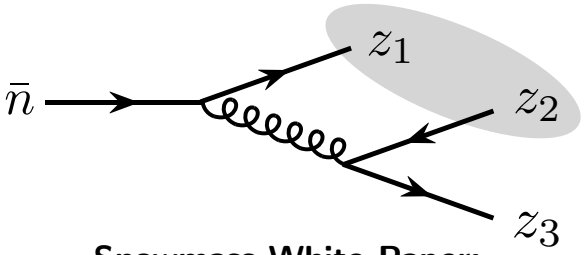
$$\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2) \sim \sum \theta^{\tau_i - 4}\mathbb{O}_i(\hat{n}_1)$$

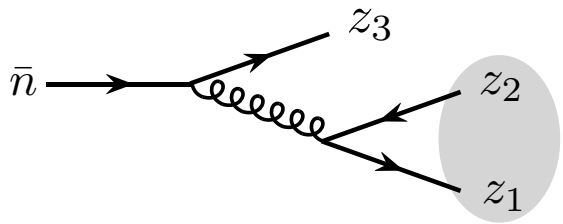
[Hofman, Maldacena]
[Chang, Kologlu, Kravchuk, Simmons Duffin, Zhiboedov]
[See Also: Konishi, Ukawa, Veneziano]

- Progress in CFT provided an understanding of the $\mathbb{O}_i$ in the OPE.
- Allows a reformulation of jet substructure as the study of the symmetry and OPE structure of these operators.

Connecting Fields

- Provides a direct connection between recent developments in (Lorentzian) CFT and real world collider physics!





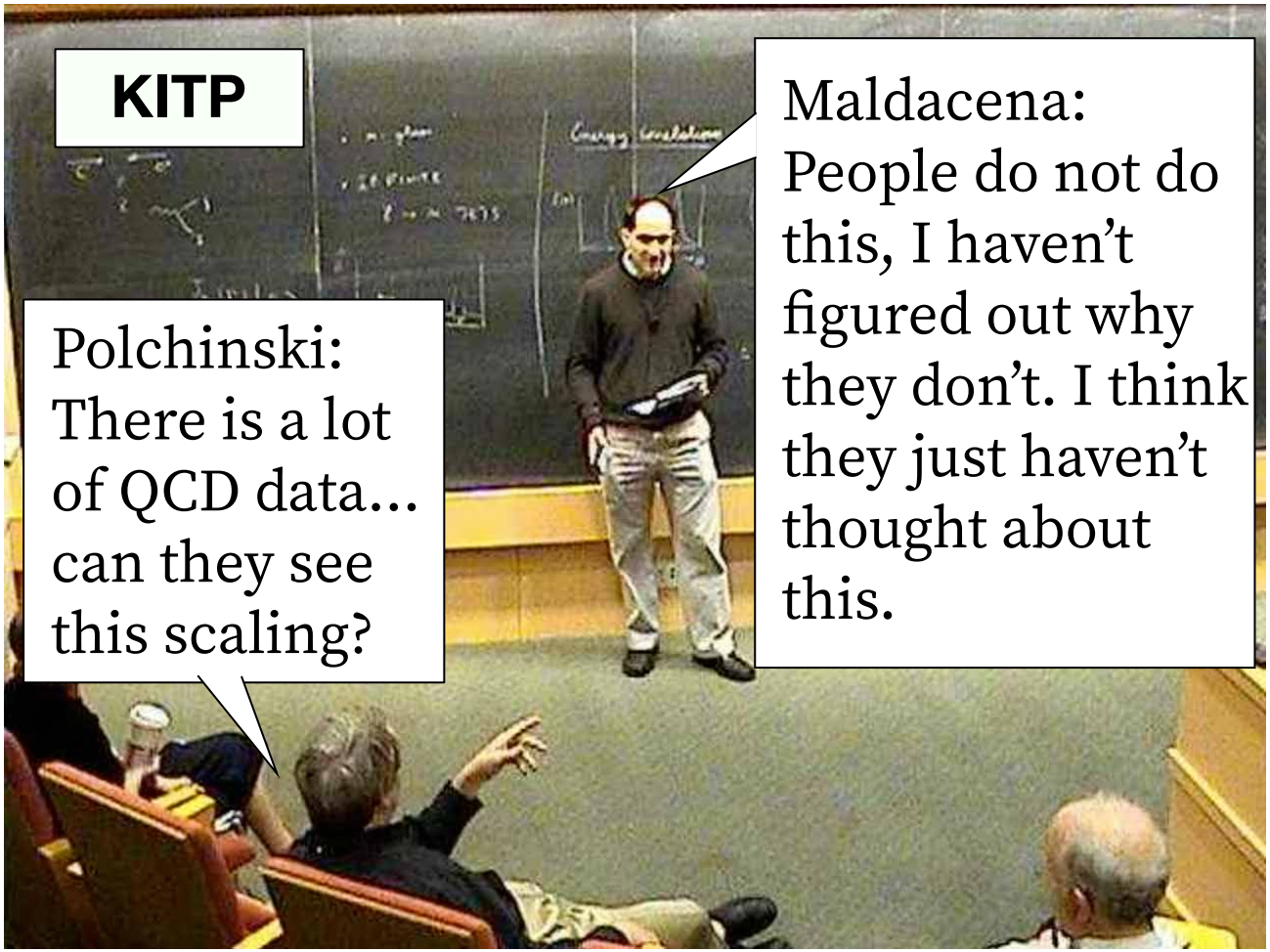
Snowmass White Paper: The Analytic Conformal Bootstrap

Thomas Hartman,[1] Dalimil Mazáč,[2] David Simmons-Duffin,[3] Alexander Zhiboedov[4]

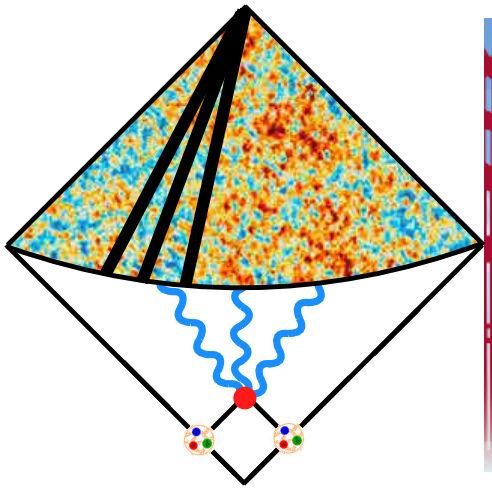
Remarkably, the machinery of the OPE [49, 65, 71, 72] and crossing equations [24, 25] can be generalized to light-ray operators in a nontrivial way. The light-ray OPE has interesting applications in the study of jet substructure in QCD [73, 74]. Developing a better understanding of the space of light-ray operators and associativity of the light-ray OPE is an important open problem in our quest for understanding nonperturbative Lorentzian dynamics of CFTs.

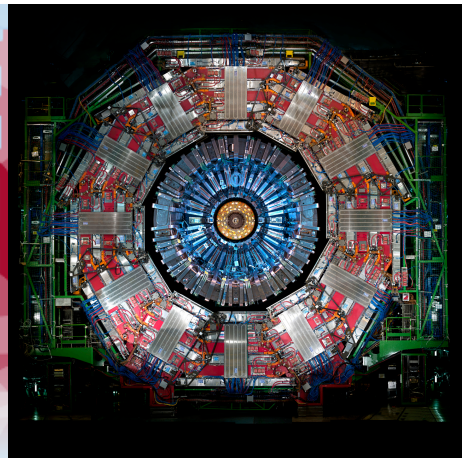
- Perturbative data from Jet Substructure calculations has played an important role in developing the light-ray OPE.

Theory-Experiment Gap



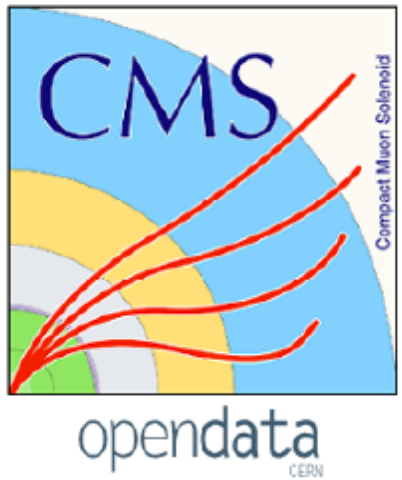
Open Data as the Bridge Between Theory and Experiment





Open Data

- A primary driver of recent progress in jet substructure has been the availability of Open Data.

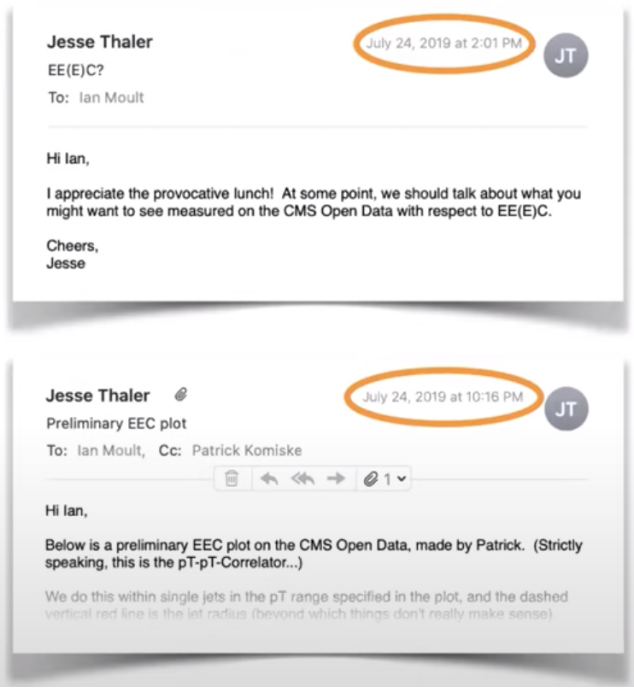


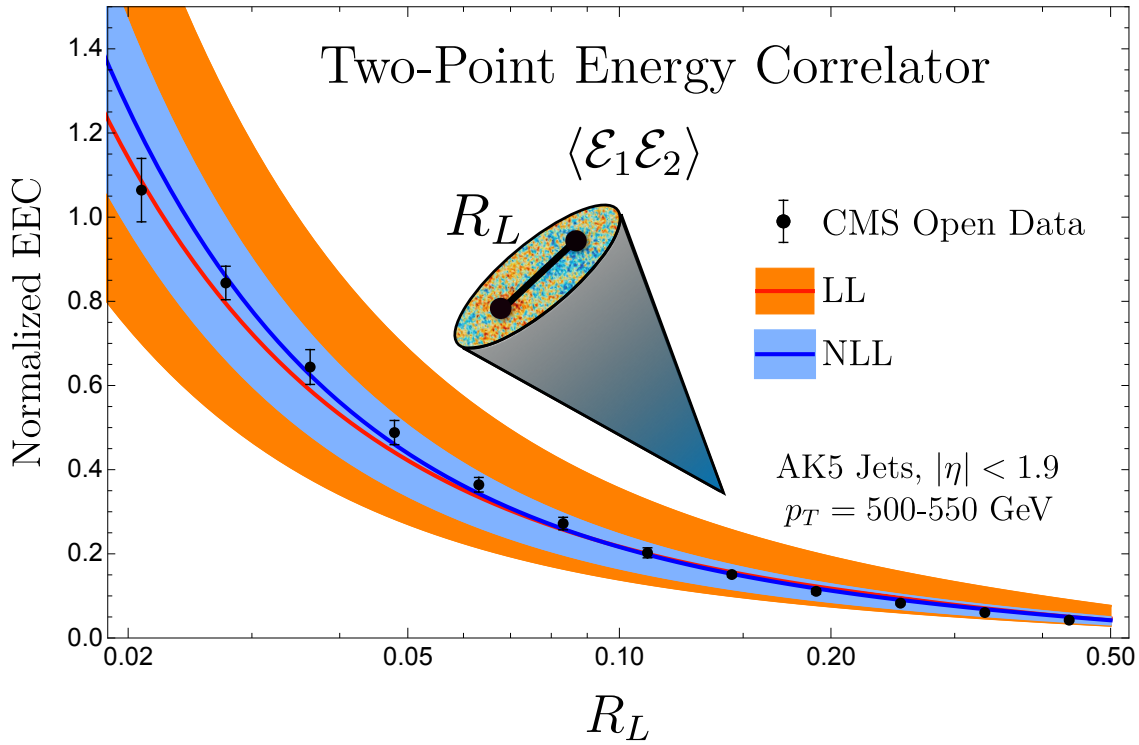
- Short-circuits the traditional path from formal theory development to collider physics applications:
  - Enables rapid transport of ideas from "theory world" to "real world".
  - Can illustrate that new approaches are phenomenologically viable.
  - Provides tests on real data for observables where standard simulations can't be trusted $\Longrightarrow$ learn new features of QCD.

Open Data

[Komiske, Moult, Thaler, Zhu]
[Dixon, Moult, Zhu]
[Lee, Mecaj, Moult]

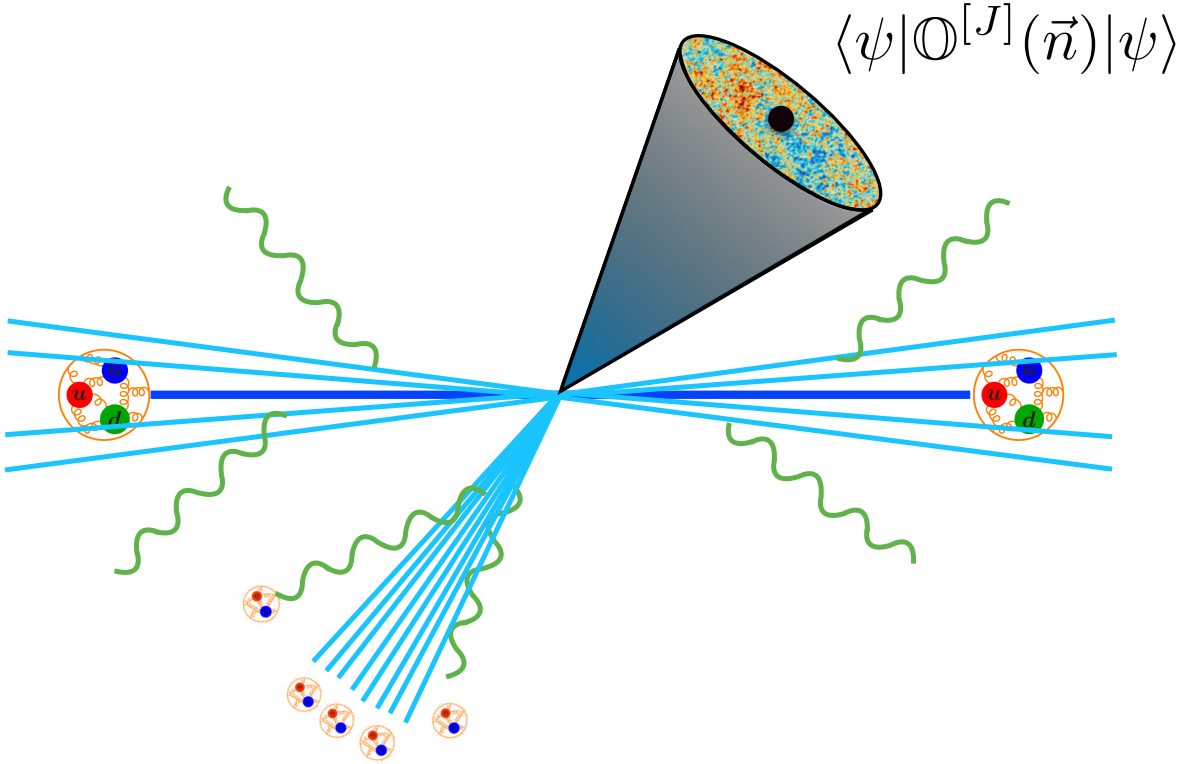
- Open Data in Action: The $\mathcal{E}(\hat{n}_1)\mathcal{E}(\hat{n}_2)$ OPE inside high-energy jets!





- An observable never before considered in LHC jets, can be analyzed from scratch in one afternoon, and used to verify a never before tested OPE in QFT! And initiate a new direction in Jet Substructure!

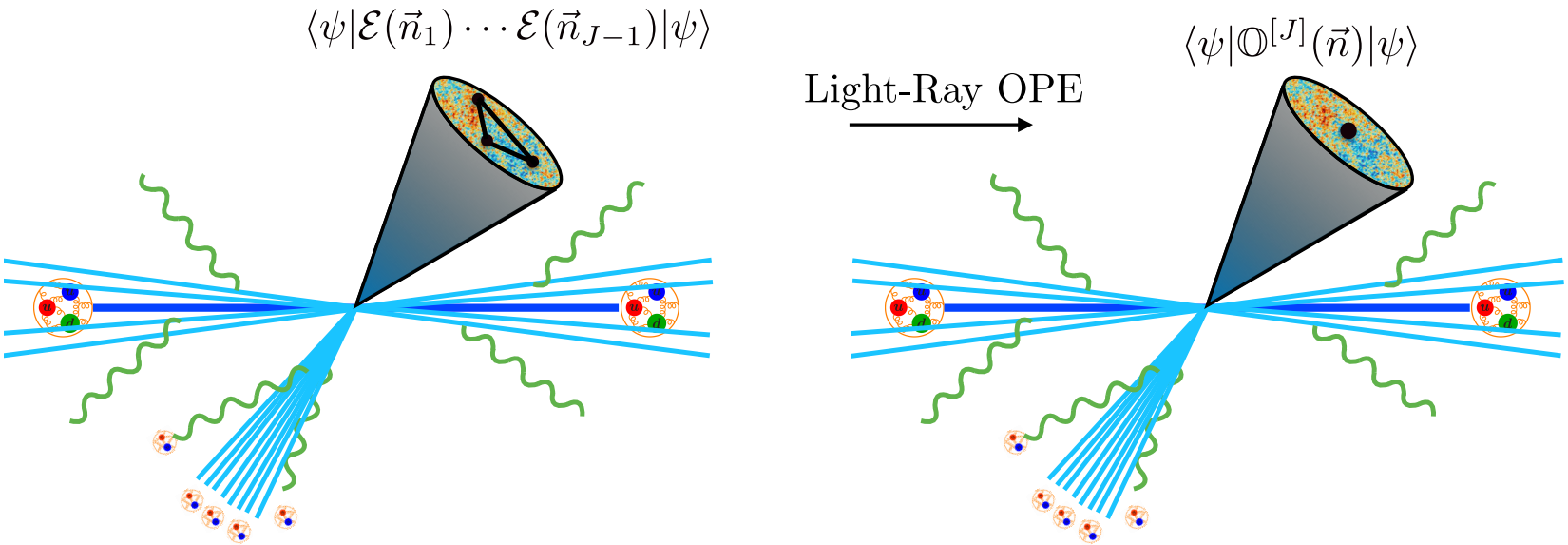
Jet Substructure as a Precision Science



Precision Jet Substructure

- Reformulation in terms of field theoretic operators allows one to replace heuristic jet shapes with sharp probes of the underlying theory:

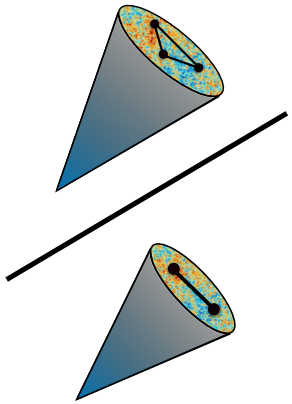
  1. Directly relates observables and field theoretic quantities.
  2. Opens the door to the use of techniques from formal theory for calculations in collider environments.



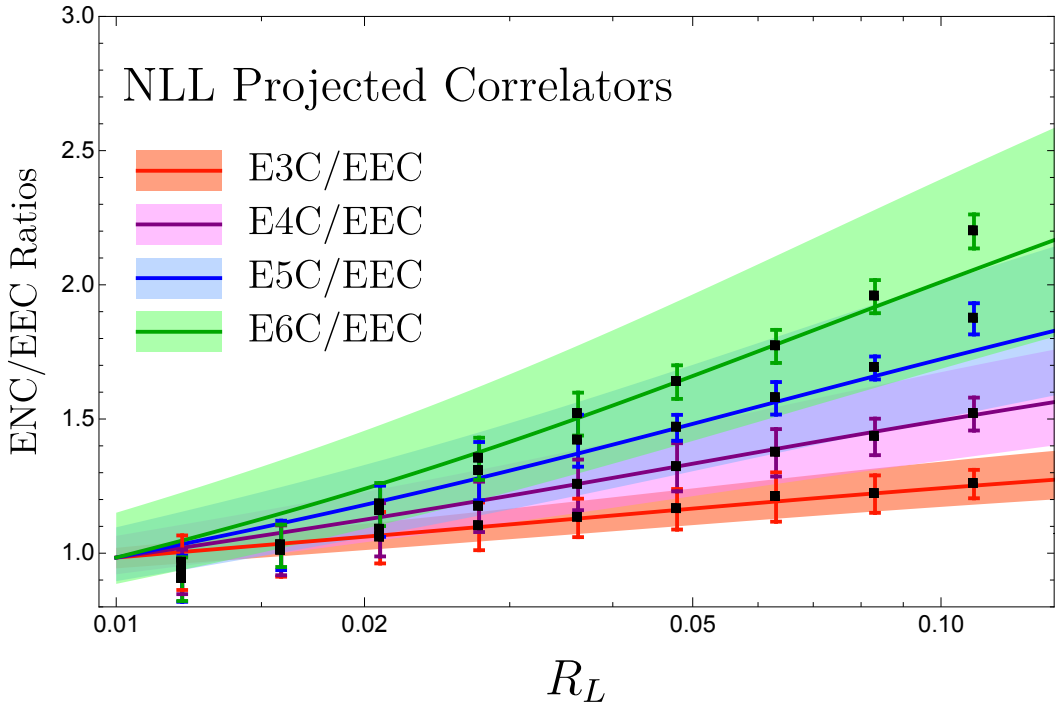
The Spectrum of a Jet

[Chen, Moult, Zhang, Zhu]
[Lee, Mecaj, Moult]

- Measurements of asymptotic energy flux directly extract the spectrum of (twist-2) lightray operators in QCD at the quantum level!



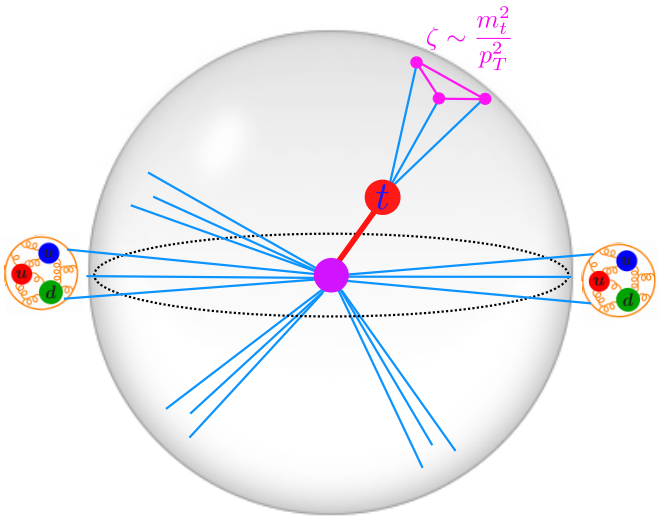
$$\frac{\langle \mathcal{E}_1 \mathcal{E}_2 \cdots \mathcal{E}_{J-1} \rangle}{\langle \mathcal{E}_1 \mathcal{E}_2 \rangle} \sim \frac{\langle \mathbb{O}^{[J]} \rangle}{\langle \mathbb{O}^{[3]} \rangle}$$

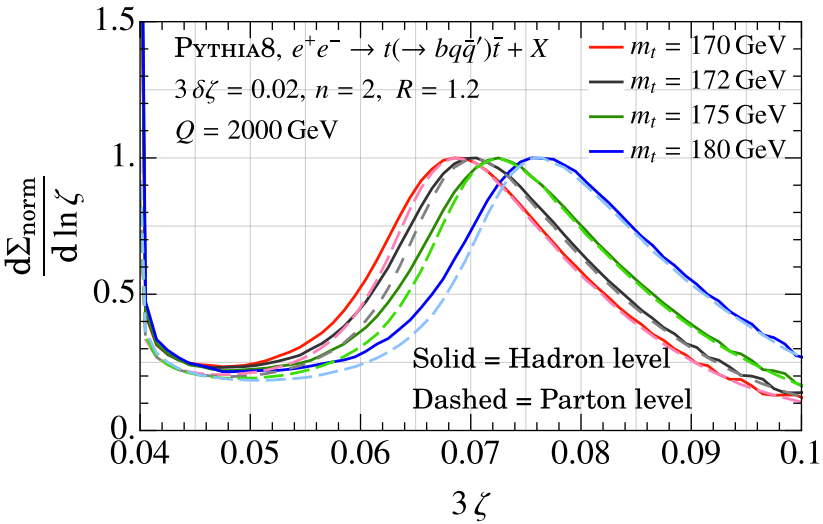


- A never before observed feature of QFT, accessible due to the high energies and remarkable detectors of the LHC.

Application I: Top Quark Mass Measurement

- The top quark mass is a central parameter of the SM.
- Mass measurements are subtle: need observables with top mass sensitivity that can be computed from first principles field theory.
- Massive particles break the scaling of the correlators and imprint their existence at a characteristic angular scale $\zeta \sim m^2/Q^2$.

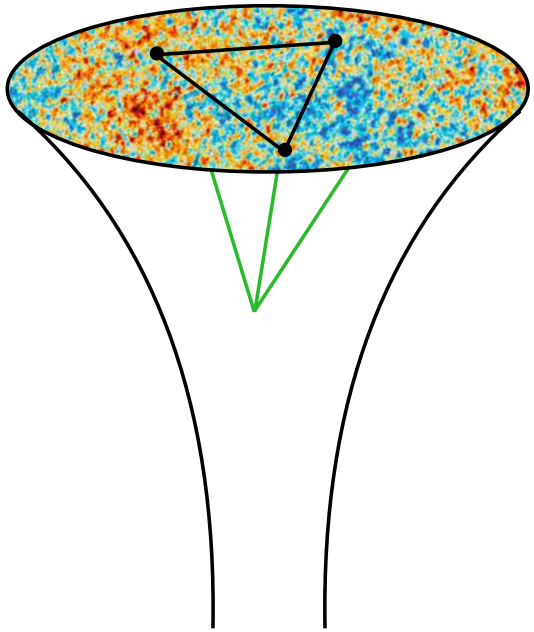


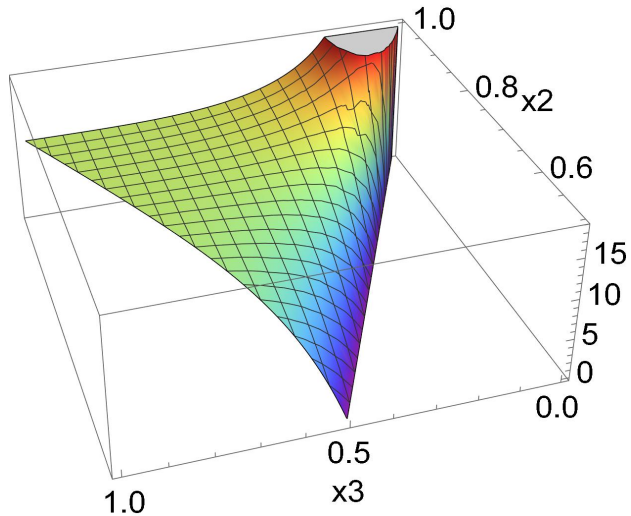


- Optimistic for a precision ($\lesssim 1$ GeV) top mass extraction at LHC from jet substructure! [Holguin, Moult, Pathak, Procura]

Shape Dependence

- Scaling probes the spectrum, but higher-point correlators probe more detailed aspects of interactions.
- e.g. Non-Gaussianities allow one to distinguish models of inflation.



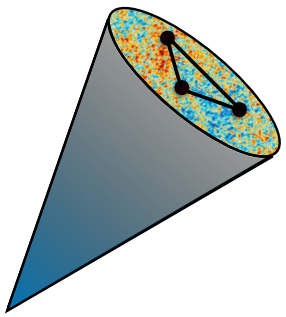


[Cabass, Pajer, Stefanysyzn, Supel]

- Can we compute higher-point functions of energy flux?

Shape Dependence of Non-Gaussianities in Data

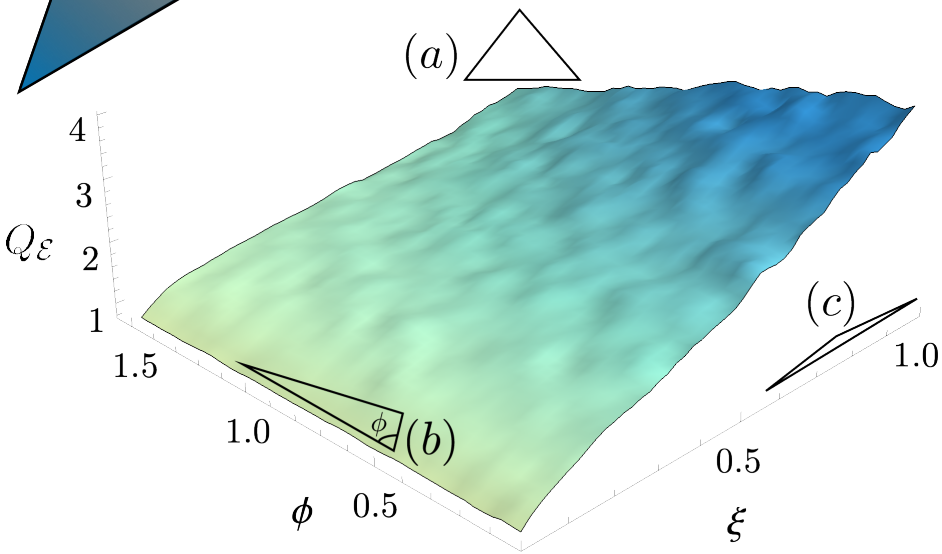
- Can directly study non-gaussianities inside high energy jets.

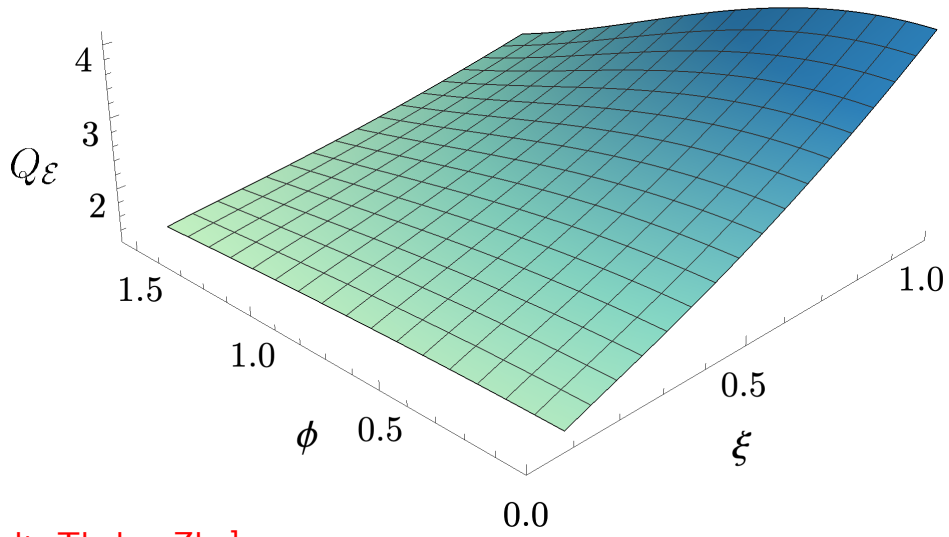


Open Data, $R_L \in (0.3, 0.4)$

$$G_{N=4}(z) = \frac{1+u+v}{2uv}(1+\zeta_2) - \frac{1+v}{2uv}\log(u) - \frac{1+u}{2uv}\log(v)$$
$$-(1+u+v)(\partial_u+\partial_v)\Phi(z) + \frac{(1+u^2+v^2)}{2uv}\Phi(z) + \frac{(z-\bar{z})^2(u+v+u^2+v^2+u^2v+uv^2)}{4u^2v^2}\Phi(z)$$
$$+\frac{(u-1)(u+1)}{2uv^2}D_2^+(z) + \frac{(v-1)(v+1)}{2u^2v}D_2^+(1-z) + \frac{(u-v)(u+v)}{2uv}D_2^+\left(\frac{z}{z-1}\right)$$

LL + LO prediction, $R_L = 0.35$



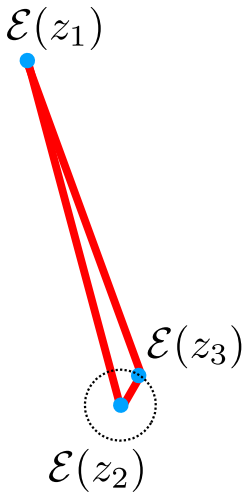


[Chen, Moult, Thaler, Zhu]

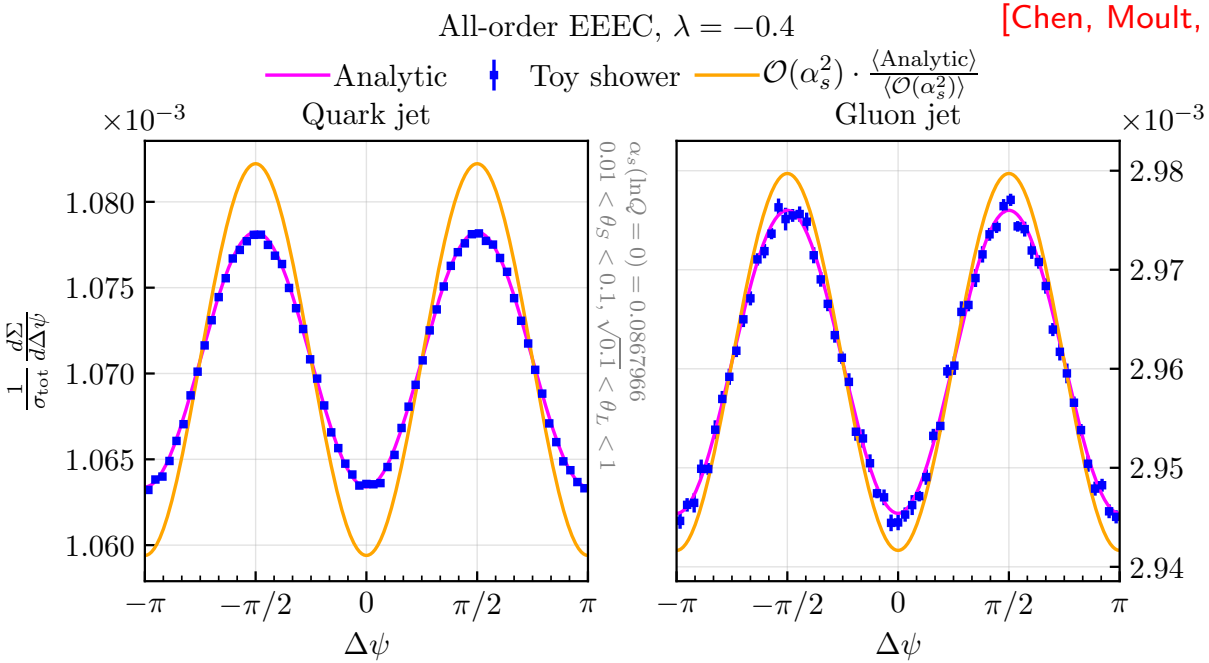
- Illustrates theoretical control over multi-point correlations!

Application II: Parton Shower Development

- Illustrates complete control of three-point correlations in jets.
- Crucial for validating implementations of higher order effects in parton showers. e.g. Spin Correlations (transverse spin operators)



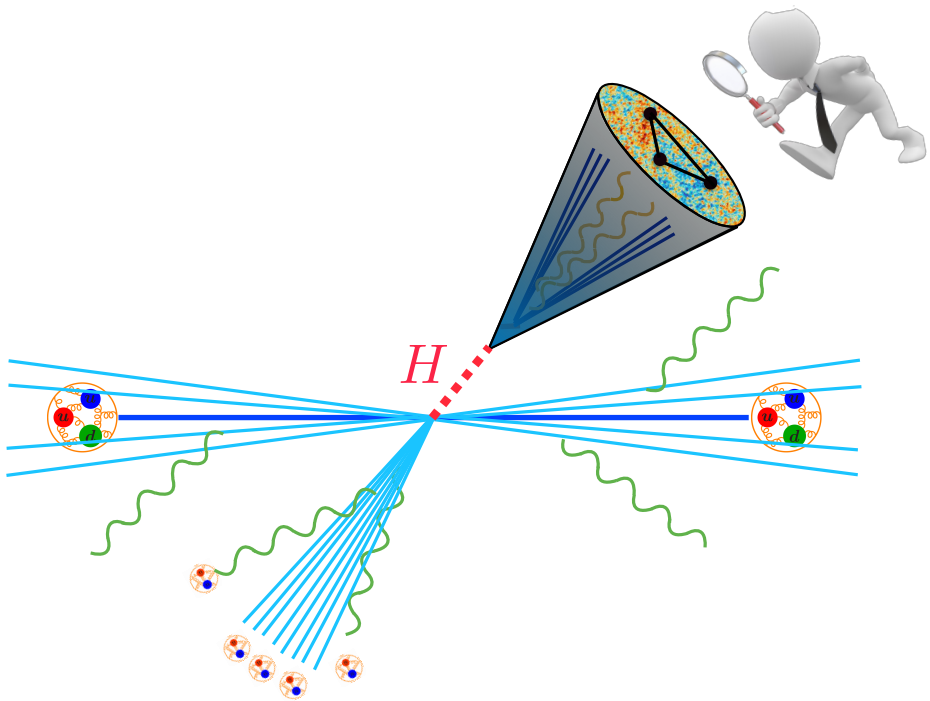
[Chen, Moult, Zhu]



[Karlberg, Salam, Scyboz, Verheyen]

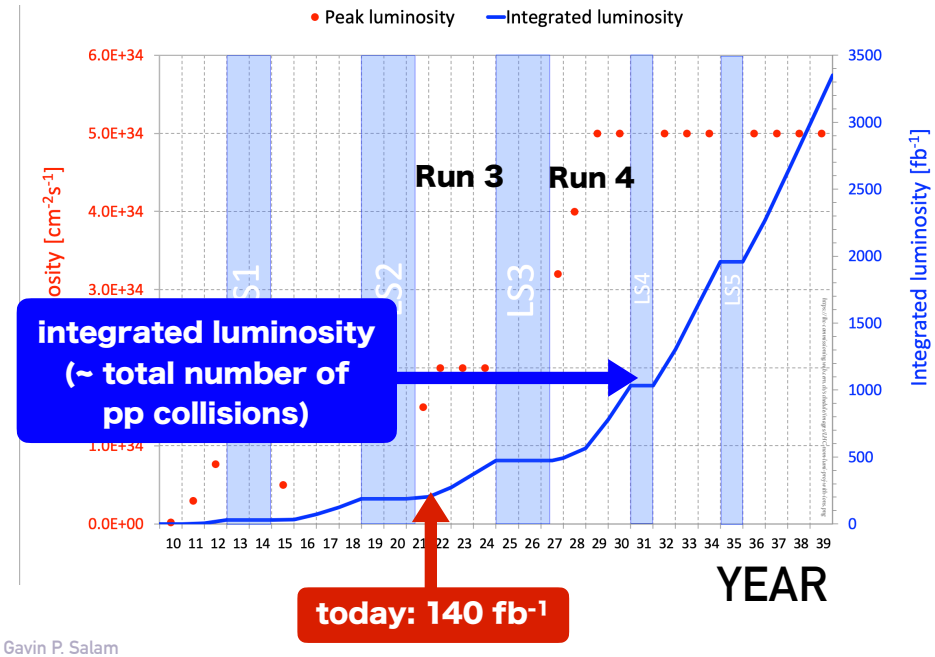
- Full incorporation of higher-point correlations in parton showers plays an important role in enhancing the LHC search program.

Fundamental Physics from QCD + Machine Learning



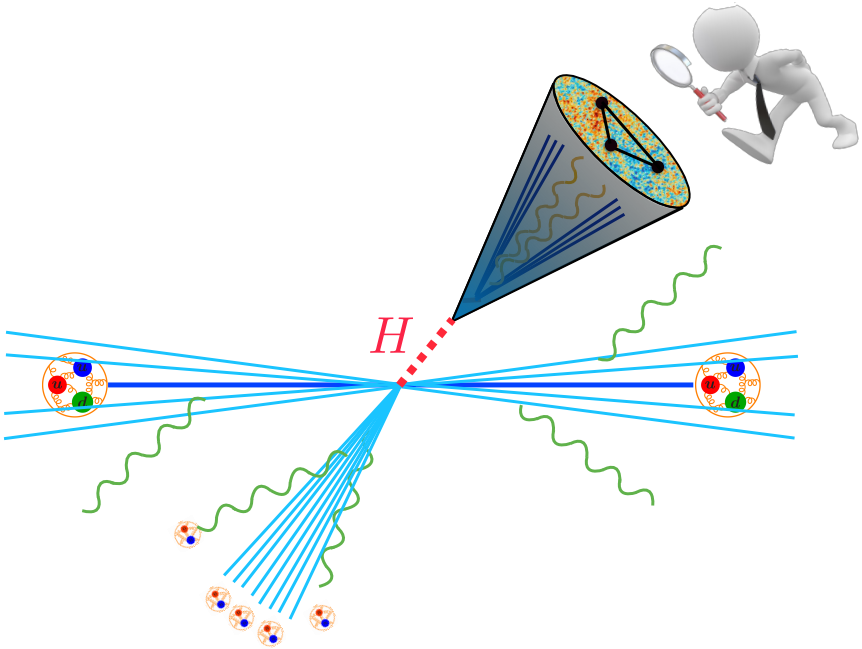
Jet Substructure: Searches

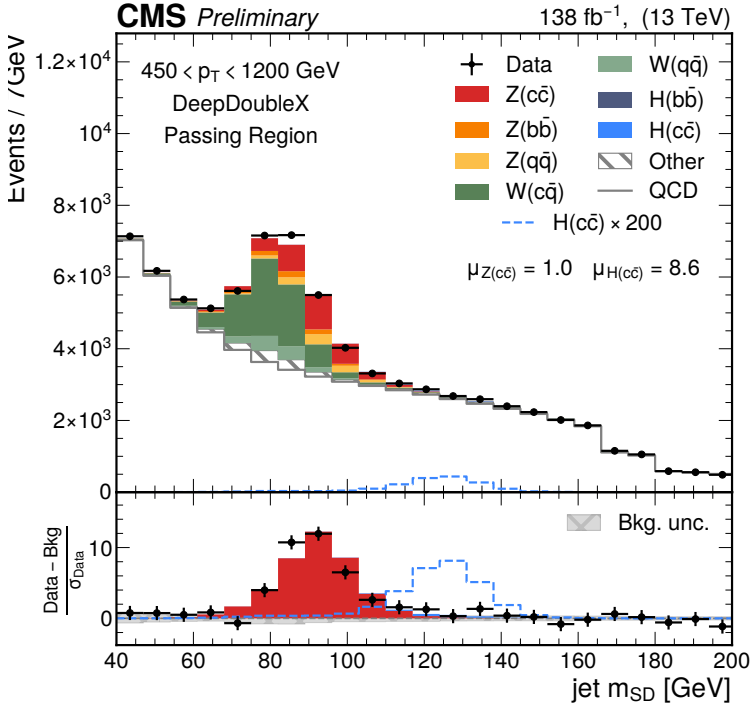
- The combination of an improved description of the "fine structure" of jets and modern Machine Learning continues to drive innovative search strategies at the LHC.
- Jet Substructure will benefit immensely from the population of ever more extreme phase space regions with high luminosity.
- Luminosity is only a relevant metric if no one learns anything between now and 2040.



Jet Substructure: Searches

- Measurements of the Higgs couplings to light quarks provide a crucial test of the Yukawa sector of the SM.
- Jet substructure (ParticleNet) provides the current most stringent bound on the charm Yukawa, $1.1 < \kappa_c < 5.5$.

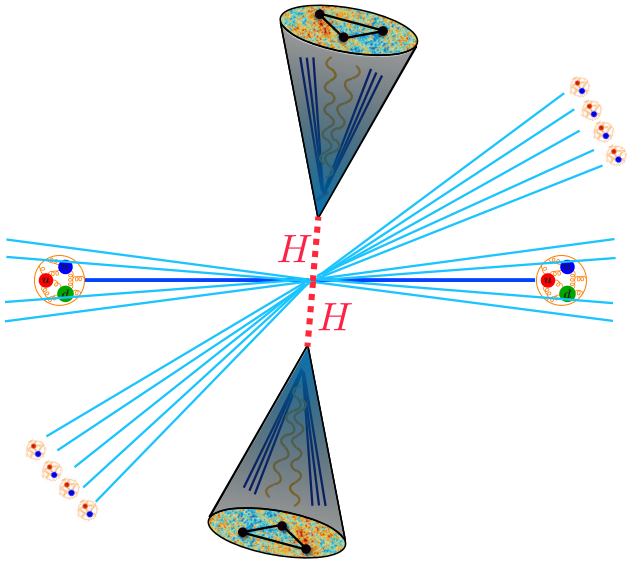


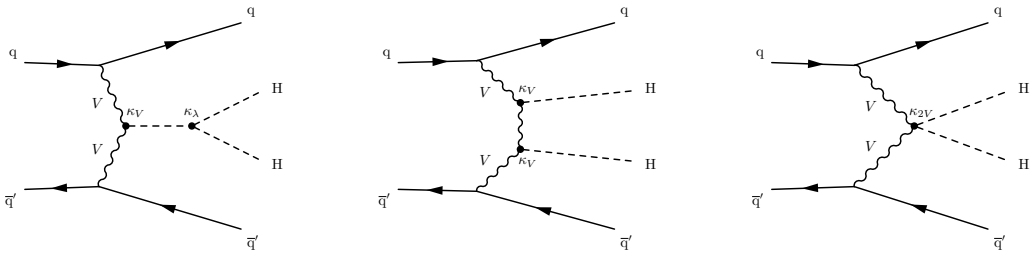


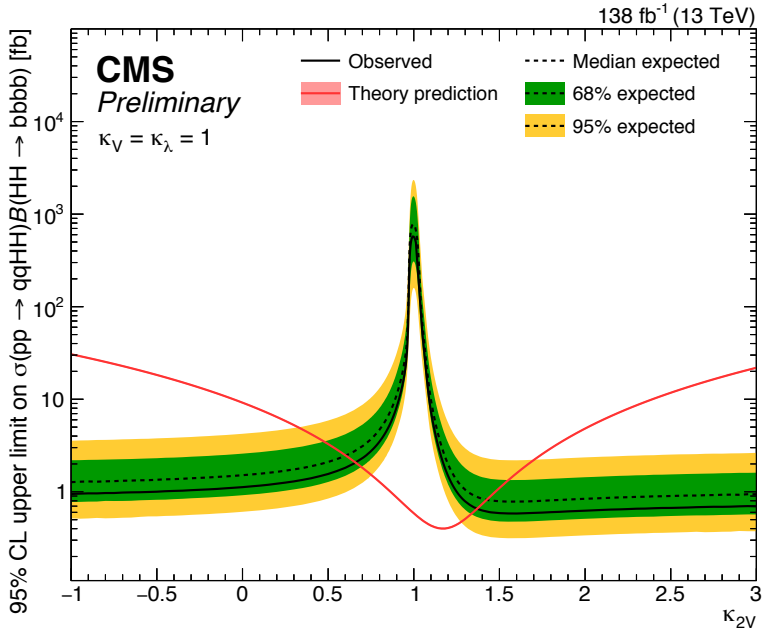
- Matches the original projected sensitivity with 3000 fb^{-1}!

Jet Substructure: Searches

- The Higgs self interaction accesses the Higgs potential.
- Jet Substructure exploits the high branching ratio to b-quarks.

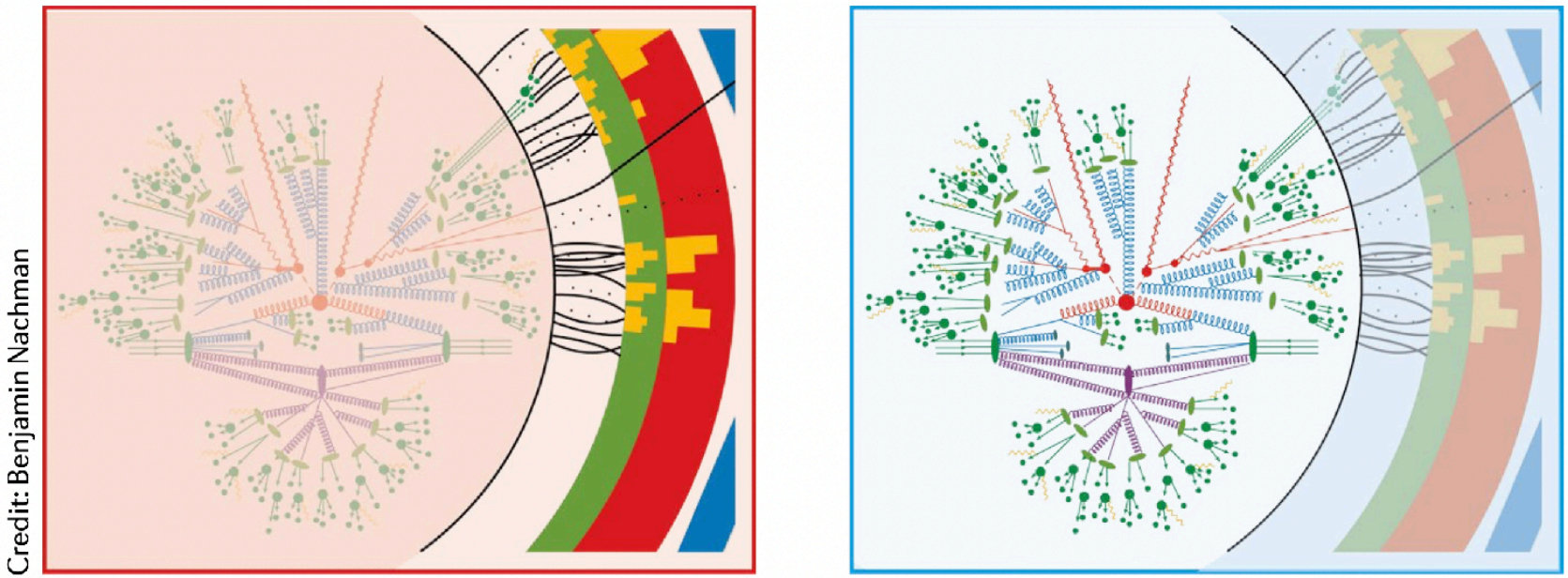






- First observation of the $VV \to HH$ coupling in the SM!

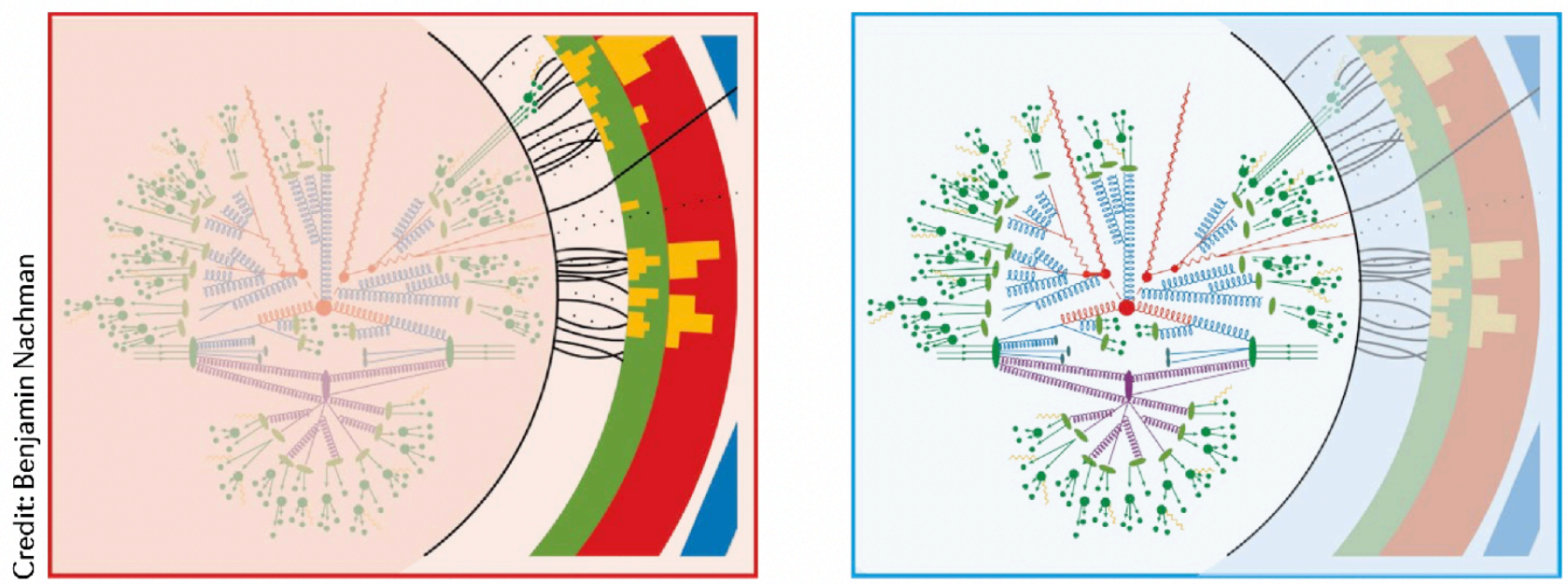
Machine Learning for Quantum Chromodynamics



Credit: Benjamin Nachman

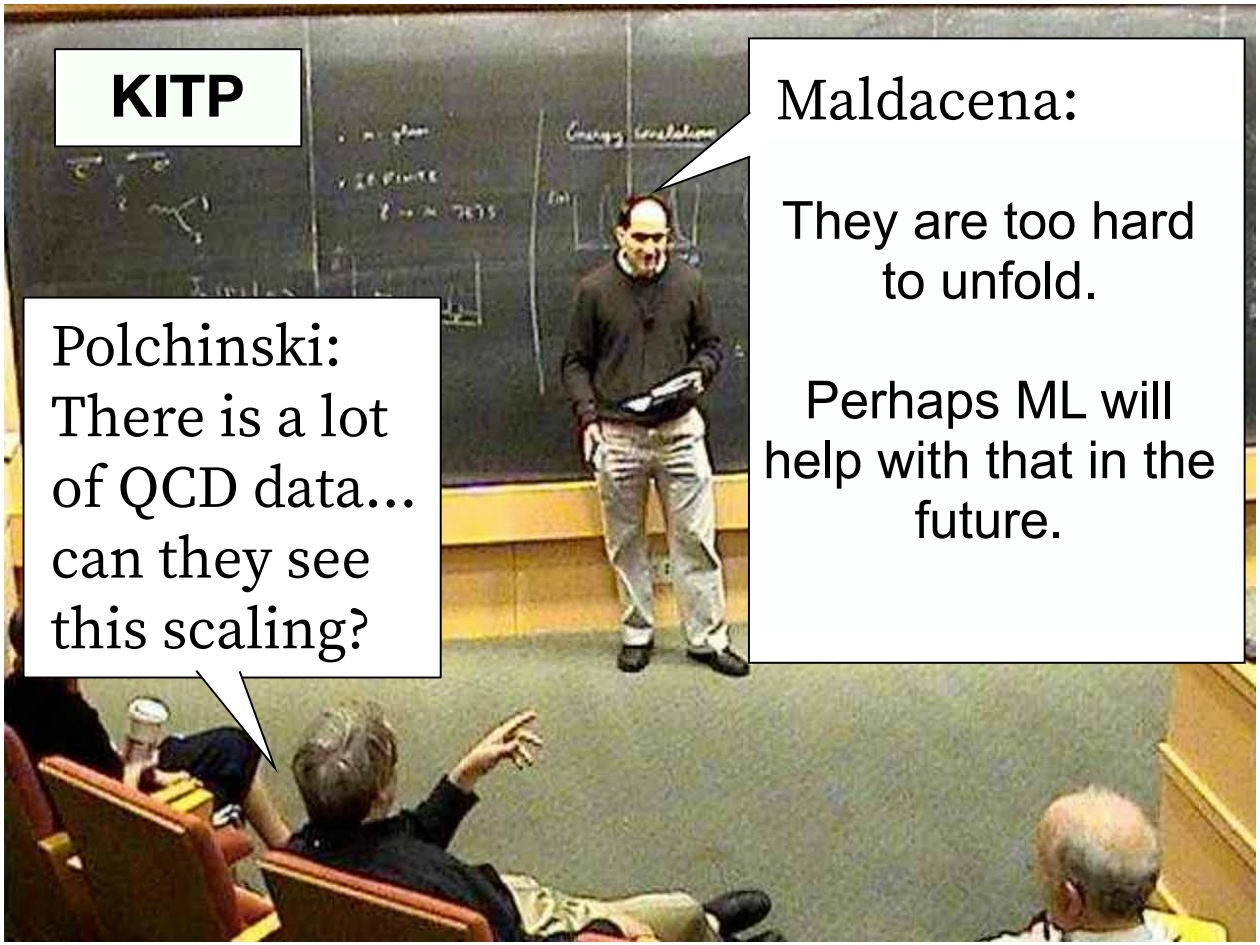
From Detector Data to Theory Comparisons

- To be interpreted theoretically, measurements must "invert" the effects of the detector: Unfolding.
- "Simple" if one projects to low dimensional features such as jets.
- To measure statistical properties of energy flux requires unfolding the full particle phase space.



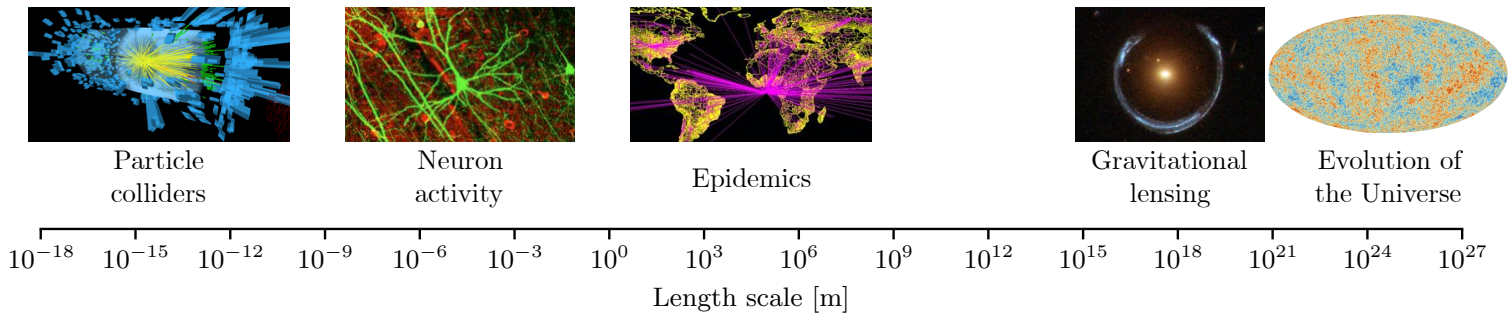
Theory-Experiment Gap

- The extraordinary complexity of the LHC dataset, has produced a gap between what theorists want, and what can be measured.



Likelihood Free Inference

- Traditional approaches to unfolding that explicitly determine the likelihood fail:
  - High dimensional input space - full phase space of detector effects.
  - High dimensional output space - space of energy correlations.
- This is a common feature of many modern data sets in the physical sciences, for which we have high fidelity simulations:
  $\Longrightarrow$ rapidly developing field of "Likelihood Free Inference"

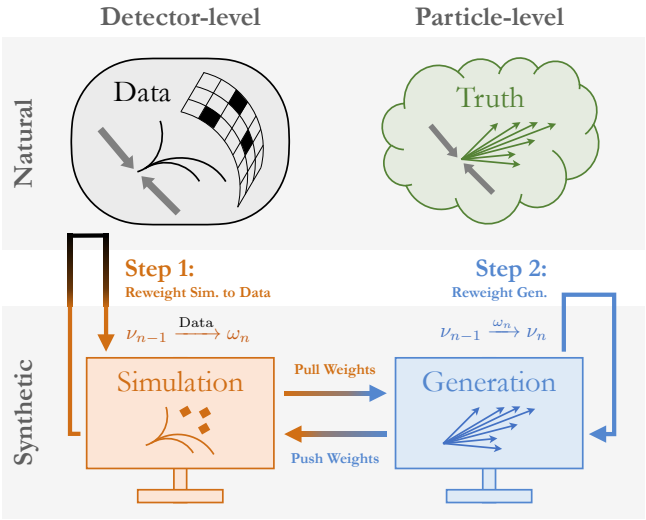


[Cranmer, Brehmer, Louppe]
[Karagiori, Kasieczka, Kravitz, Nachman, Shih]

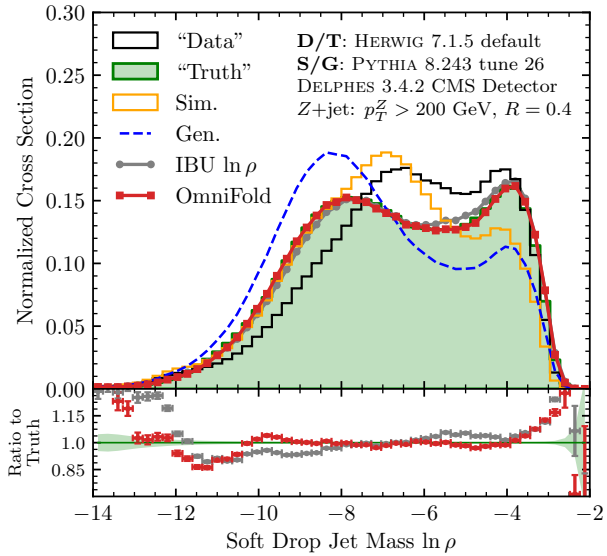
- Gaining popularity in collider physics, and surpassing the wide variety of "Inference Free ML" approaches.

Omnifold

- Seminal advance in unfolding for collider physics: Omnifold

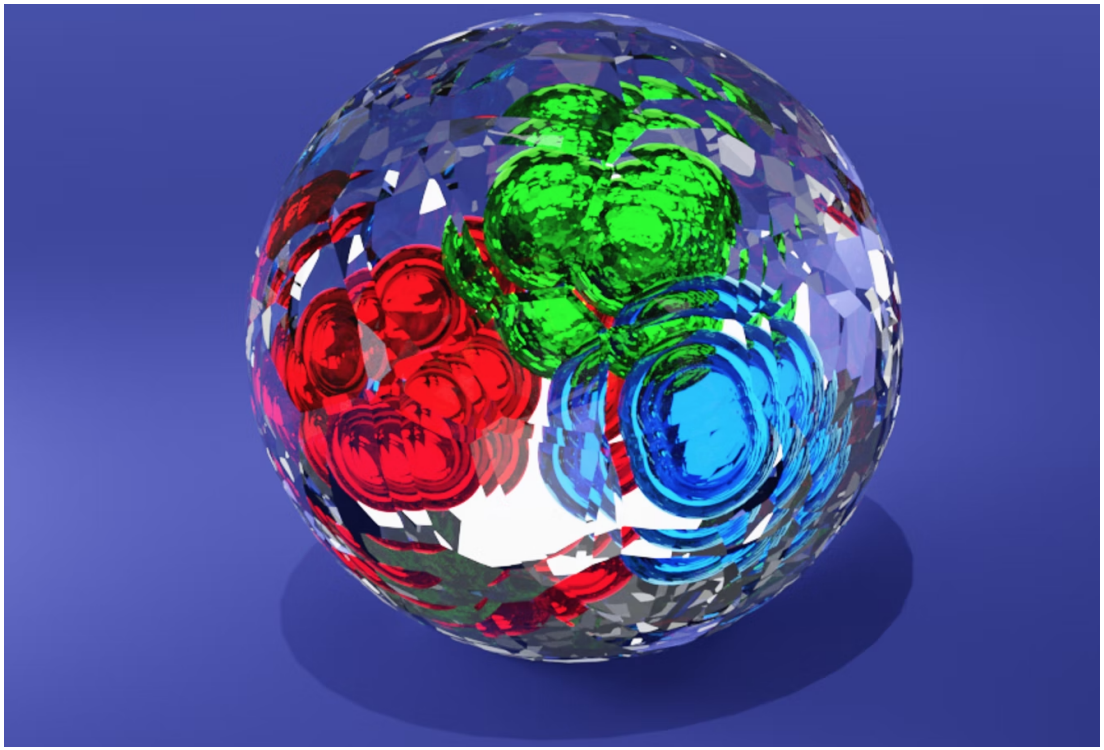


[Andreassen, Nachman]
[Andreassen, Komiske, Metodiev, Nachman, Thaler]



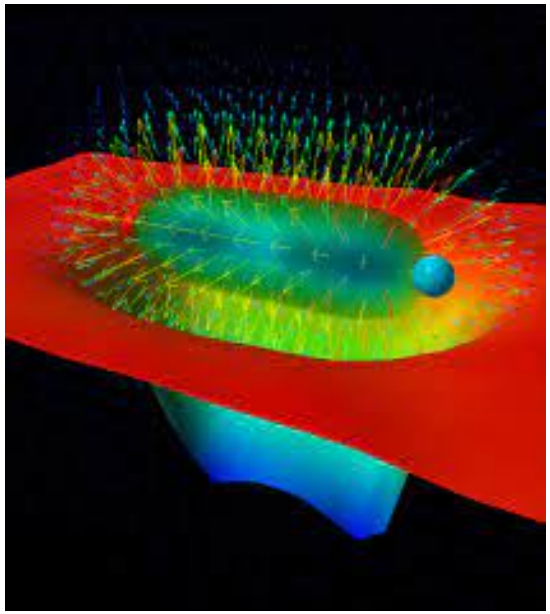
- Rigorously proven to reduce to Iterative Bayesian Unfolding.
- Explicit expression for likelihood intractable in high dimension
  $\Longrightarrow$ circumvented by classification task.
- Unfolding of qualitatively new observables (Energy Correlators), combined with theory progress $\Longrightarrow$ transformative progress in QCD.

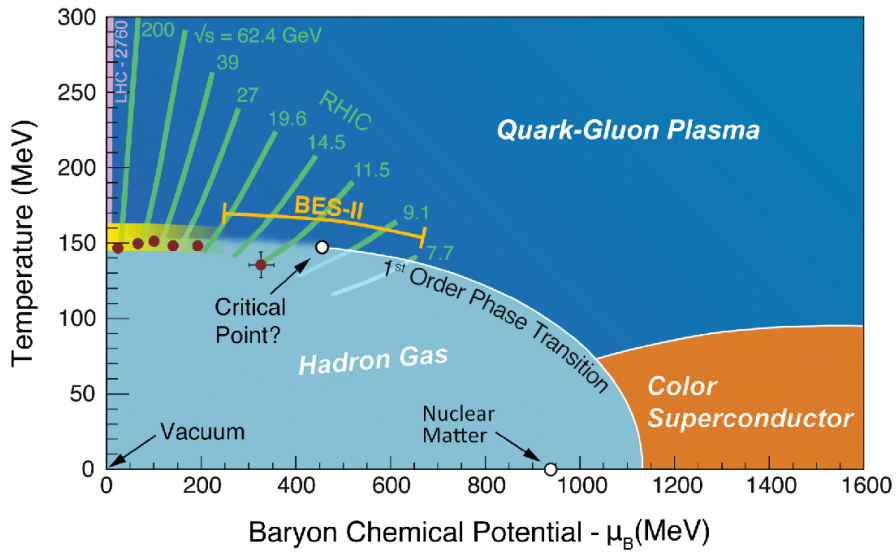
The Frontiers of Quantum Chromodynamics



Confinement in Quantum Chromodynamics

- The theory of the strong interactions is a pillar of modern physics.
- Confinement is one of the most important open problems in fundamental physics: will require combined theory-experiment effort.

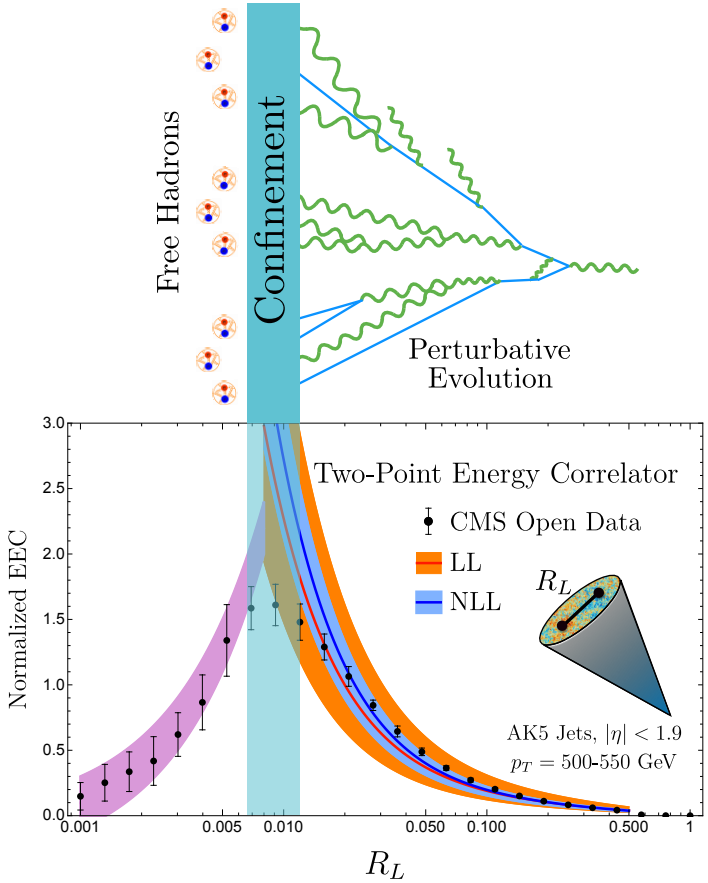


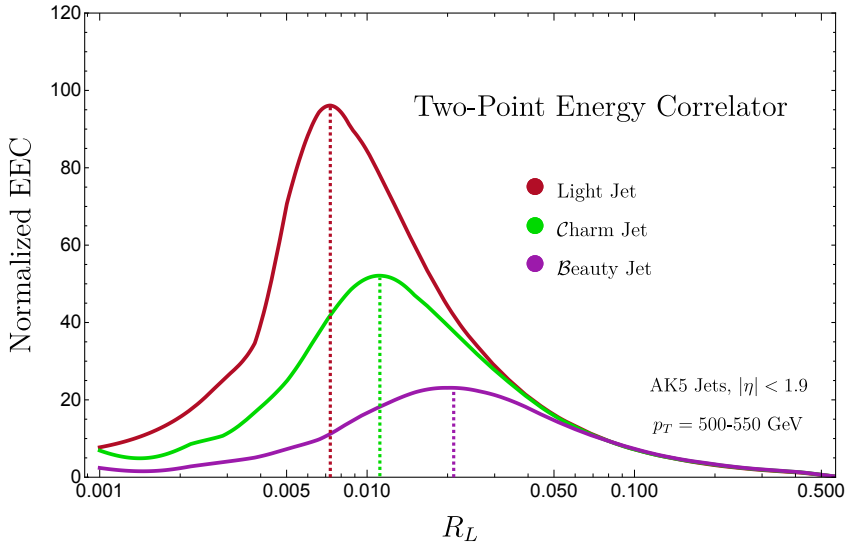


- Colliders offer a unique experimental handle on confinement in QCD through the production of asymptotically free quarks and gluons in jets, or the Quark Gluon Plasma.

The Confinement Transition

- Energy correlators allow the hadronization process to be directly imaged inside high energy jets.



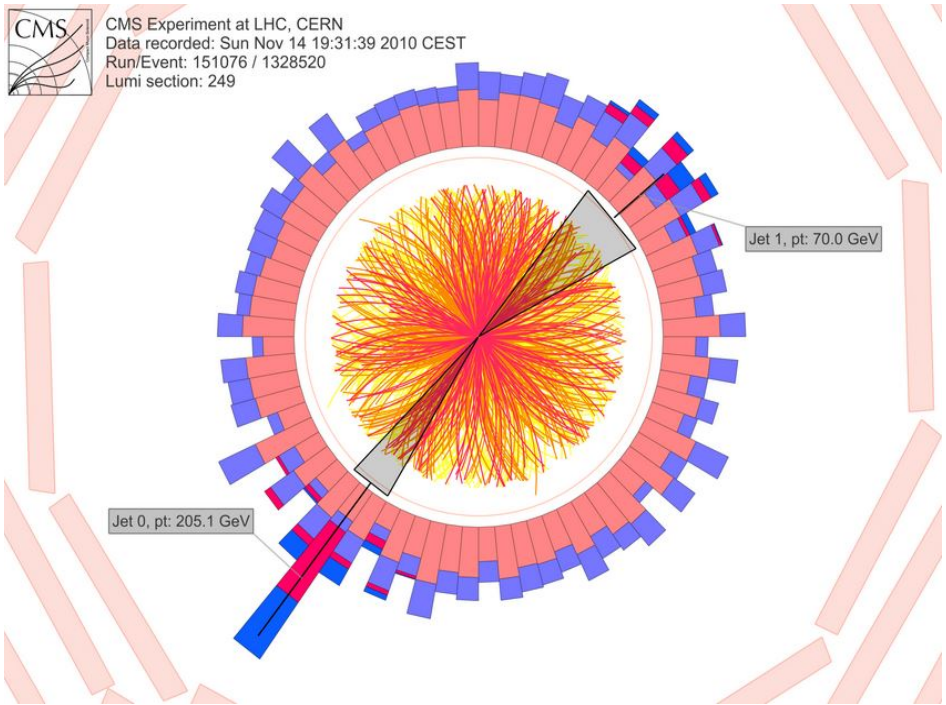


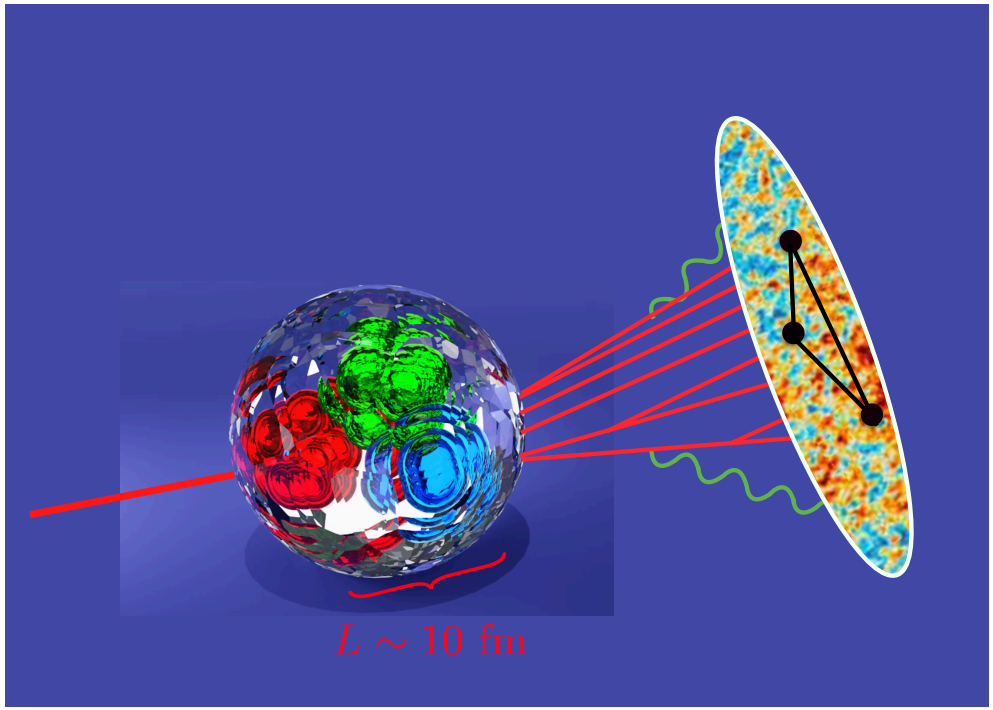
[Lee, Mecaj, Moult]

- Studying the transition for heavy mesons/baryons/onia will provide new insights into confinement.

From Jets to Jet Substructure in Heavy Ion

- Resolving the mystery of how asymptotically free quarks and gluons conspire to form a strongly coupled fluid is a primary goal of the heavy ion program.

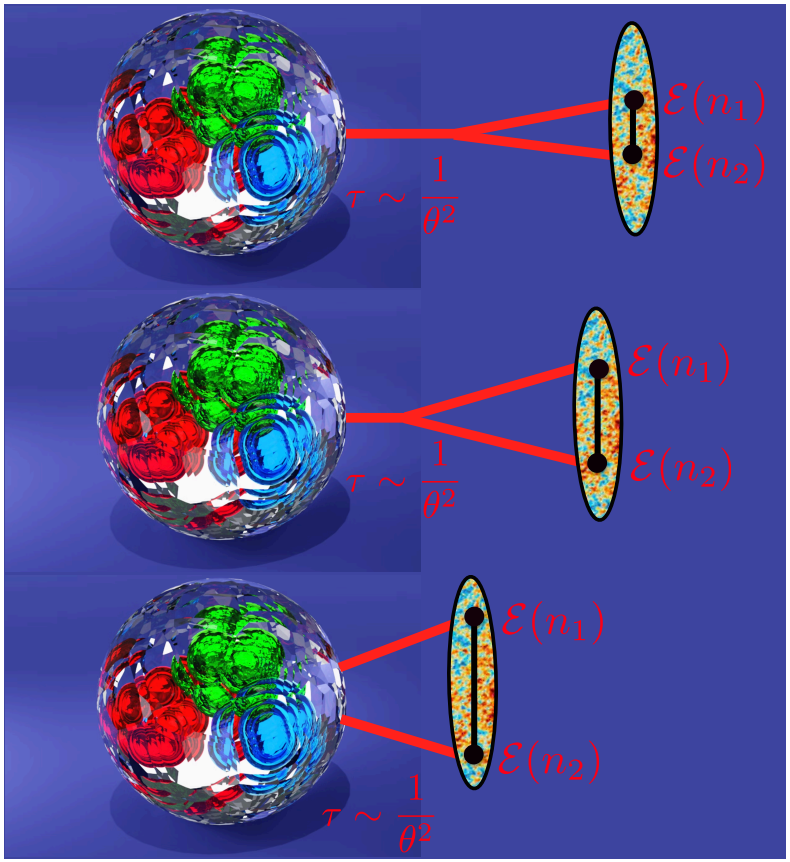




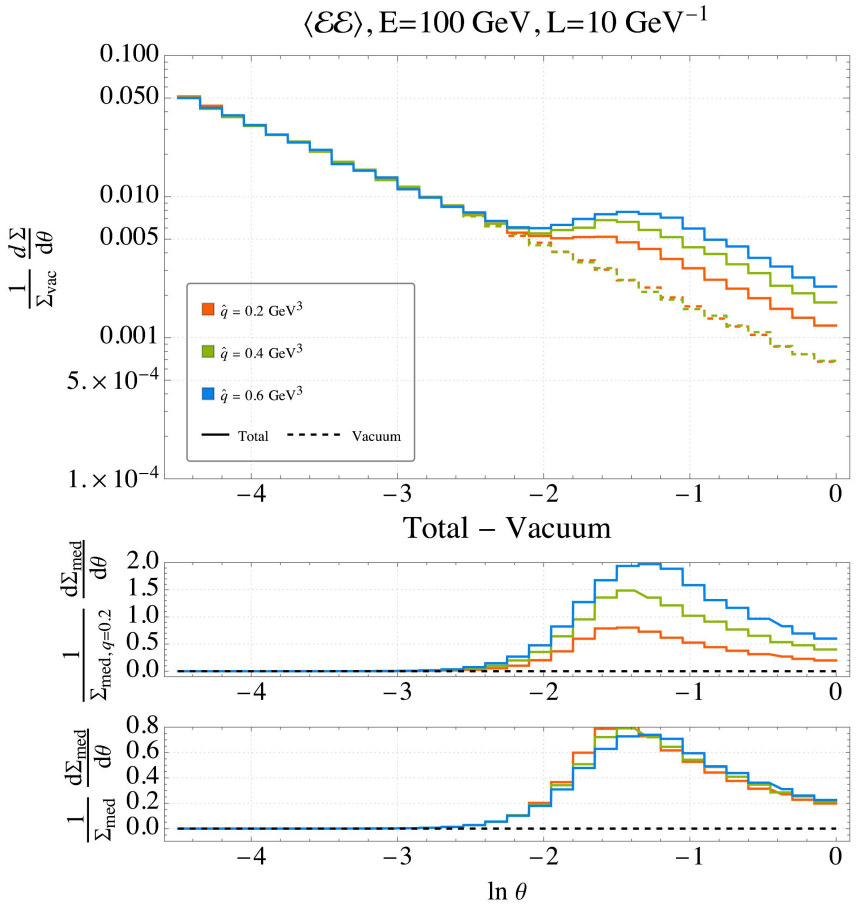
- Jets are multi-scale probes $\Longrightarrow$ scales of the QGP are imprinted at characteristic scales in the substructure of jets.

Resolving the Scales of the QGP

- QGP scales cleanly imprinted in two-point correlation.



Increasing θ

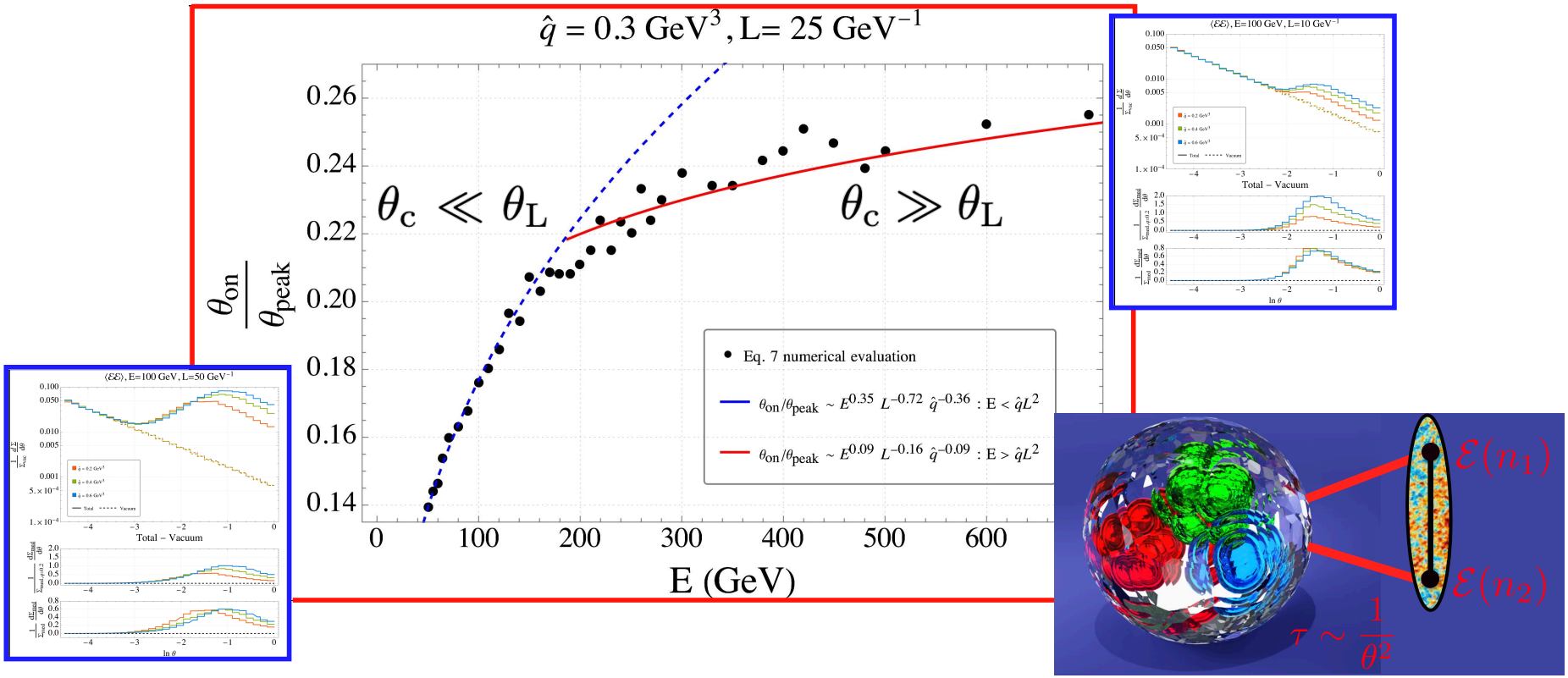


Increasing θ

[Andres, Dominguez, Holguin, Kunnawalkam Elayavalli, Marquet, Moult]

Resolving the Scales of the QGP

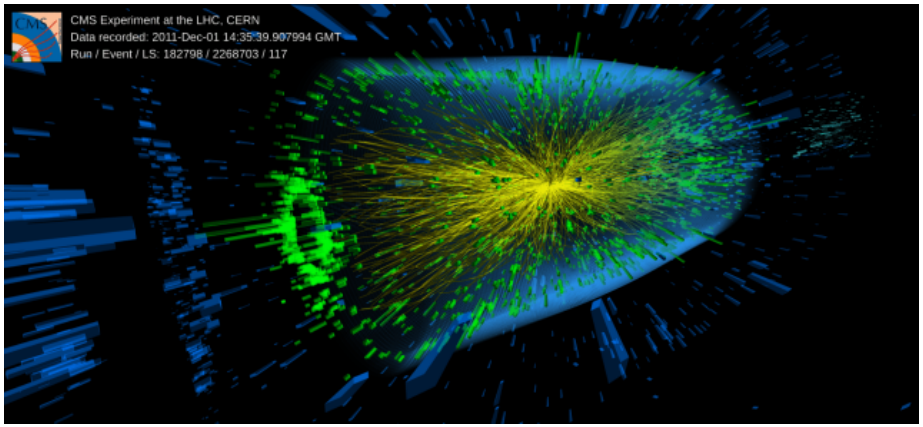
- Detailed shape of the transition can extract whether the medium interacts with the partons in the jet coherently.

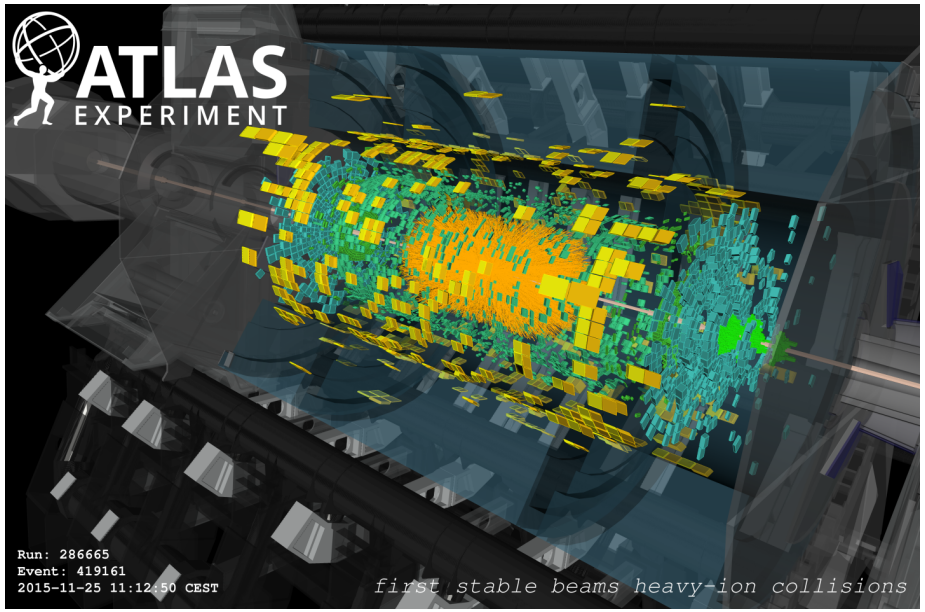


- Jet Substructure provides a new lens through which to view the QGP.

The Convergence of Heavy Ion and HEP

- The heavy ion programs at the LHC will continue to blur the lines between traditional HEP and Nuclear Theory.

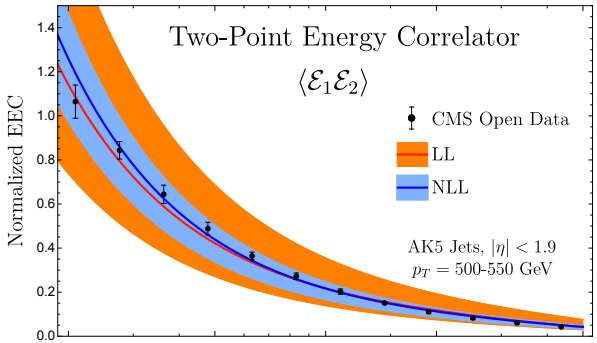




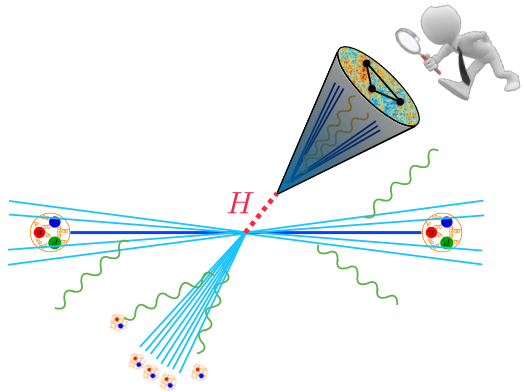
- Increasing use of approaches (theory and data analysis) from HEP, with certainty for feedback into searches.
- To fully exploit this remarkable dataset for fundamental HEP research will require a more synergistic approach.

Summary

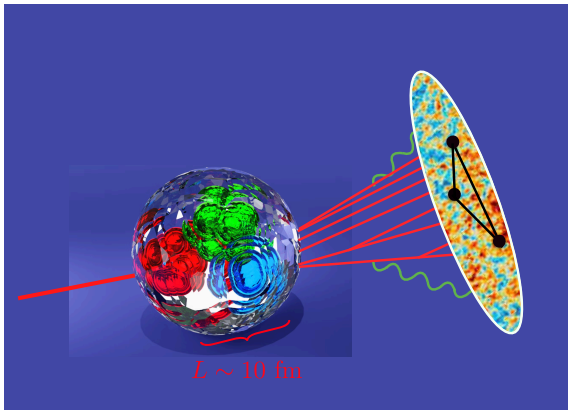
- Formal theory has transformed how and what we compute in Jet Substructure.



- Collider physics inextricably ties Data Science and Quantum Field Theory.

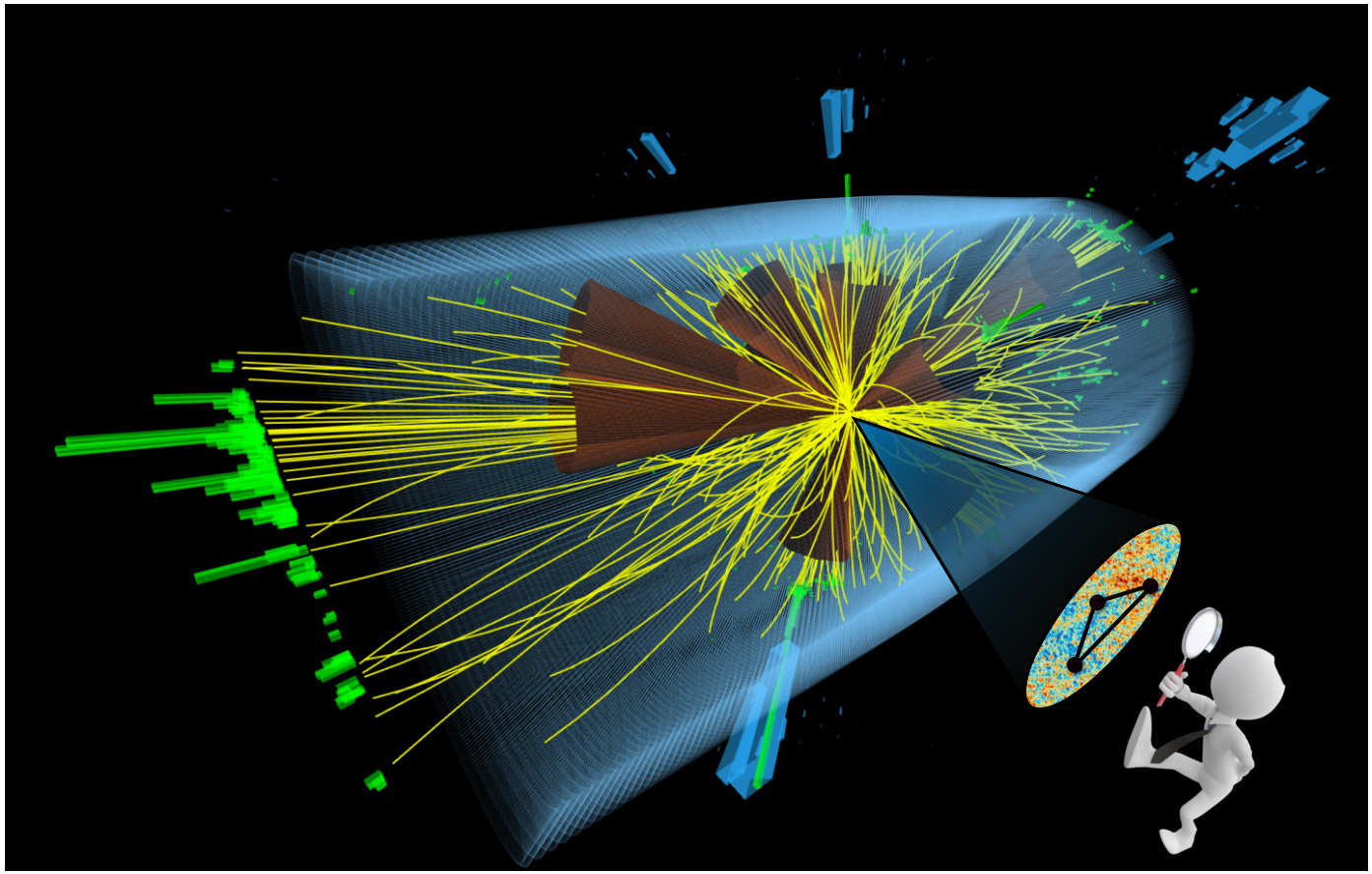


- Confinement remains a pressing open problem in fundamental physics experimentally accessible only by colliders.



Summary

- Jet Substructure continues to push the boundaries of collider physics.



- We look forward to the exciting projects from the Snowmass Process.


Thanks!